ORBITAL TRANSFER VEHICLE

CONCEPT DEFINITION AND SYSTEMS ANALYSIS STUDY

FINAL REPORT – PHASE I
VOLUME III

SYSTEM AND PROGRAM TRADES
1986

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AND

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FOREWORD

This final report of the Orbital Transfer Vehicle (OTV) Concept Definition and System Analysis Study was prepared by Boeing Aerospace Company for the National Aeronautics and Space Administration's George C. Marshall Space Flight Center in accordance with Contract NAS8-36107. The study was conducted under the direction of the NASA OTV Study Manager, Mr. Donald Saxton, during the period from 1984 to September 1986.

This final report is organized into the following nine documents:

VOL. I   Executive Summary (Rev. A)

VOL. II   OTV Concept Definition & Evaluation

                 Book 1 - Mission Analysis & System Requirements

                 Book 2 - OTV Concept Definition

                 Book 3 - Subsystem Trade Studies

                 Book 4 - Operations and Propellant Logistics

VOL. III   System & Program Trades

VOL. IV   Space Station Accommodations

VOL. V   WBS & Dictionary

VOL. VI   Cost Estimates

VOL. VII   Integrated Technology Development Plan

VOL. VIII   Environmental Analysis

VOL. IX   Implications of Alternate Mission Models and Launch Vehicles

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ACRONYMS AND ABBREVIATIONS

ACC	Aft Cargo Carrier
AFE	Aeroassist Flight Experiment
AGE	Aerospace Ground Equipment
AL	Aluminum
ASE	Airborne Support Equipment
A/T	Acceptance Test, Auxiliary Tank
AUX	Auxiliary
AVG	Average
B/B	Ballute Brake
B/W	Backwall
CDR	Critical Design Review
CPU	Central Processing Unit
CUM	Cumulative
DAK	Double Aluminized Kapton
DDT&E	Design, Development, Test & Evaluation
DELIV	Delivery
DMU	Data Management Unit
DoD	Department of Defense
EPS	Electrical Power System
FACIL	Facility
FFC	First Flight Certification
FLTS	Flights
FOSR	Flexible Optical Surface Reflector
FRCI	Fiber Refractory Composite Insulation
F.S.	Fail Safe
FSI	Flexible Surface Insulation
FTA	Facilities Test Article
GB	Ground Based
GEO	Geostationary Earth Orbit
GPS	Global Positioning System
GRD	Ground
IOC	Initial Operational Capability
IRU	Inertial Reference Unit
IUS	Inertial Upper Stage

JSC	Johnson Space Center
L/B	Lifting Brake
LCC	Life Cycle Cost
L/D	Lift to Drag
MGSS	Mobile GEO Service Station
MLI	Multilayer Insulation
MPS	Main Propulsion System
MPTA	Main Propulsion Test Article
MSFC	Marshall Space Flight Center
OMV	Orbital Maneuvering Vehicle
OPS	Operations
OTV	Orbital Transfer Vehicle
PAM	Payload Assist Module, Propulsion Avionics Module
PDR	Preliminary Design Review
PFC	Preliminary Flight Certification
P/L	Payload
PROD	Production
PROP	Propellant
RCS	Reaction Control System
REF	Reference
RGB	Reusable Ground Based
R&R	Remove & Replace
RSB	Reusable Space Based
RSI	Reusable Surface Insulation
SB	Space Based
S/C	Spacecraft
SCB	Shuttle Cargo Bay
SIL	Systems Integration Laboratory
STA	Structural Test Article
STG	Stage
STS	Space Transportation System
T/D	Turndown
TDRS	Tracking Data Relay Satellite
TPS	Thermal Protection System
TT&C	Telemetry, Tracking and Control
WBS	Work Breakdown Structure

1.0 INTRODUCTION

This section provides an overview of the entire study effort in terms of background, objectives and issues, study/report organization, and content of this specific volume.

Use of trade names, names of manufacturers, or recommendations in this report does not constitute an official endorsement either expressed or implied, by the National Aeronautics and Space Administration.

And finally, it should be recognized that this study was conducted prior to the STS safety review that resulted in an STS position of "no Centaur in Shuttle" and subsequently an indication of no plans to accommodate a cryo OTV or OTV propellant dump/vent. The implications of this decision are briefly addressed in section 2.2 of Volume I and also in Volume IX reporting the Phase II effort which had the OTV launched by an unmanned cargo launch vehicle. A full assessment of a safety compatible cryo OTV launched by the Shuttle will require analysis in a future study.

1.1 BACKGROUND

Access to GEO and earth escape capability is currently achieved through the use of partially reusable and expendable launch systems and expendable upper stages. Projected mission requirements beyond the mid-1990's indicate durations and payload characteristics in terms of mass and nature (manned missions) that will exceed the capabilities of the existing upper stage fleet. Equally important as the physical shortfalls is the relatively high cost to the payload. Based on STS launch and expendable upper stages the cost of delivering payloads to GEO range from $12,000 to $24,000 per pound.

A significant step in overcoming the above factors would be the development of a highly efficient reusable upper stage. Numerous studies (ref. 1, 2, 3, 4) have been conducted during the past decade concerning the definition of such a stage and its program. The scope of these investigations have included a wide variety of system-level issues dealing with the type of propulsion to be used, benefits of aeroassist, ground- and space-basing, and impact of the launch system.

1.2 OBJECTIVES AND ISSUES

The overall objective of this study was to re-examine many of these same issues but within the framework of the most recent projections in technology readiness, realization that a space station is a firm national commitment, and a refinement in mission projections out to 2010.

The output of this effort was twofold: (1) the definition of a preferred OTV concept(s) and its programmatics, and (2) definition of the key interfaces that would occur between the OTV and Space Station.

During the first nineteen months of technical effort the specific issues addressed were:

a. What are the driving missions?

b. What are the preferred space-based OTV characteristics in terms of propulsion, aeroassist, staging, and operability features?

c. What are the preferred ground-based OTV characteristics in terms of delivery mode, aeroassist, and ability to satisfy the most demanding missions?

d. How extensive are the orbital support systems in terms of propellant logistics and Space Station accommodations?

e. Where should the OTV be based?

f. How cost effective is a reusable OTV program?

g. What are the implications of using advanced launch vehicles?

1.3 STUDY/REPORT ORGANIZATION

Accomplishment of the objectives and investigation of the issues was done considering two basic combinations of mission models and launch systems. Phase I concerned itself with a mission model having 145 OTV flights during the 1995-2010 timeframe (Rev 8. model) and relied solely on the space shuttle for launching. Phase 2 considered a more ambitious model (Rev 9) having 442 flights during the same time frame as well as use of a large unmanned cargo launch vehicle and an advanced Space Shuttle (STS II).

The study is reported in nine separate volumes. Volume I presents an overview of the results and findings for the entire study. Volume II through VIII contains material associated only with the phase I activity. Volume IX presents material unique to the phase II activity. Phase I involved five quarters of the technical effort and one quarter was associated with the Phase II analyses.

1.4 DOCUMENT CONTENT

This specific document reports the work relating to establishing overall program and system level characteristics associated with the Phase I activity. The most significant factors influencing these results were the use of the STS as the launch vehicle and the Rev 8 low mission model. The remainder of this document describes the approach used to conduct these trades; the generic trades that are generally common to

all concepts; optimization trades performed to select the best ground and space based OTV's; a summary of the station OTV accommodations and propellant logistics trades; and finally, the comparison of the baseline ground and space based OTV's to determine the preferred basing mode. In most cases, the vehicles, subsystems and technical areas being described are summary in nature however details are available in Volume II, Book 3 and 4 and Volume IV. System level trades were also performed during Phase II which involved a Rev. 9 mission model and large unmanned cargo launch vehicle. This data is reported in Volume IX.

A final note deals with the numerous iterations of some of the concepts and trades throughout the two year (6 quarters) study. As such, some material may reflect analysis completed during the second quarter while others were completed during the third, fourth or fifth quarters each with slightly different groundrules. For the most part however, only the final definition/iteration is reported.

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2.0 APPROACH AND GROUNDRULES

The approach used to conduct the system level trades is shown in the logic flow of figure 2-1. Mission analysis provided the mission profiles and velocity requirements necessary to develop point design associated with each OTV concept. Generic trades applicable to all concepts were then performed followed by optimization of each SB and GB OTV concept. Selection of the winner in these trades was primarily based on life cycle cost data which included preliminary (second quarter) station accommodations and operations inputs. The selected SB OTV concept involved trades regarding the aeroassist concept and staging. The selected SB and GB OTV concepts were then considered in several program combinations to determine the preferred basing mode. Contributing to both the SB OTV selection and basing mode trades were factors resulting from final definition of the Station accommodations and operations. The preferred OTV concept was then characterized in more detail to provide detailed cost and schedule data, an indication of the technology needs and an expression of its effectiveness relative to existing upper stages.

The key groundrules provided by NASA to be used in conducting these trades are shown in table 2-1. Cost was to be the primary factor in selecting trade winners although in some cases other factors such as risk or uncertainty were to be considered. Four cost parameters are indicated, however, we did not apply any weighting factor or priority to them. Should there be a significant DDT&E cost associated with a given option but it has the best LCC, it is desirable for it to begin its payback no later than 50% through the mission model. Trade study decisions were to be based on use of the Rev. 8 low mission model which averages approximately 8 flights per year to GEO (130,000 lbs of payload). Shuttle capability reflects use of Orbiter 104 weights, 109% SSME thrust, and filament wound cases for the SRB's. Cost per STS flight reflects a cost base after 1988 and the different flight rates of the mission models. Scavenging propellant is based on the capability of 10-12 STS flights per year for this function and use of cargo bay tanks. The IOC's of the OTV's reflect the earliest possible date considering development durations and in addition the SB OTV must await the growth version of Space Station.

The mission models used in performing the trades is presented in table 2-2. A key factor contributing to each trade is the size of vehicle involved in terms of propellant loading. An indication of the propellant required for the principal missions in the low model is shown in figure 2-2. The indicated propellant needs are for a SB single stage ballute braked OTV however the other investigated concepts have similar values. It
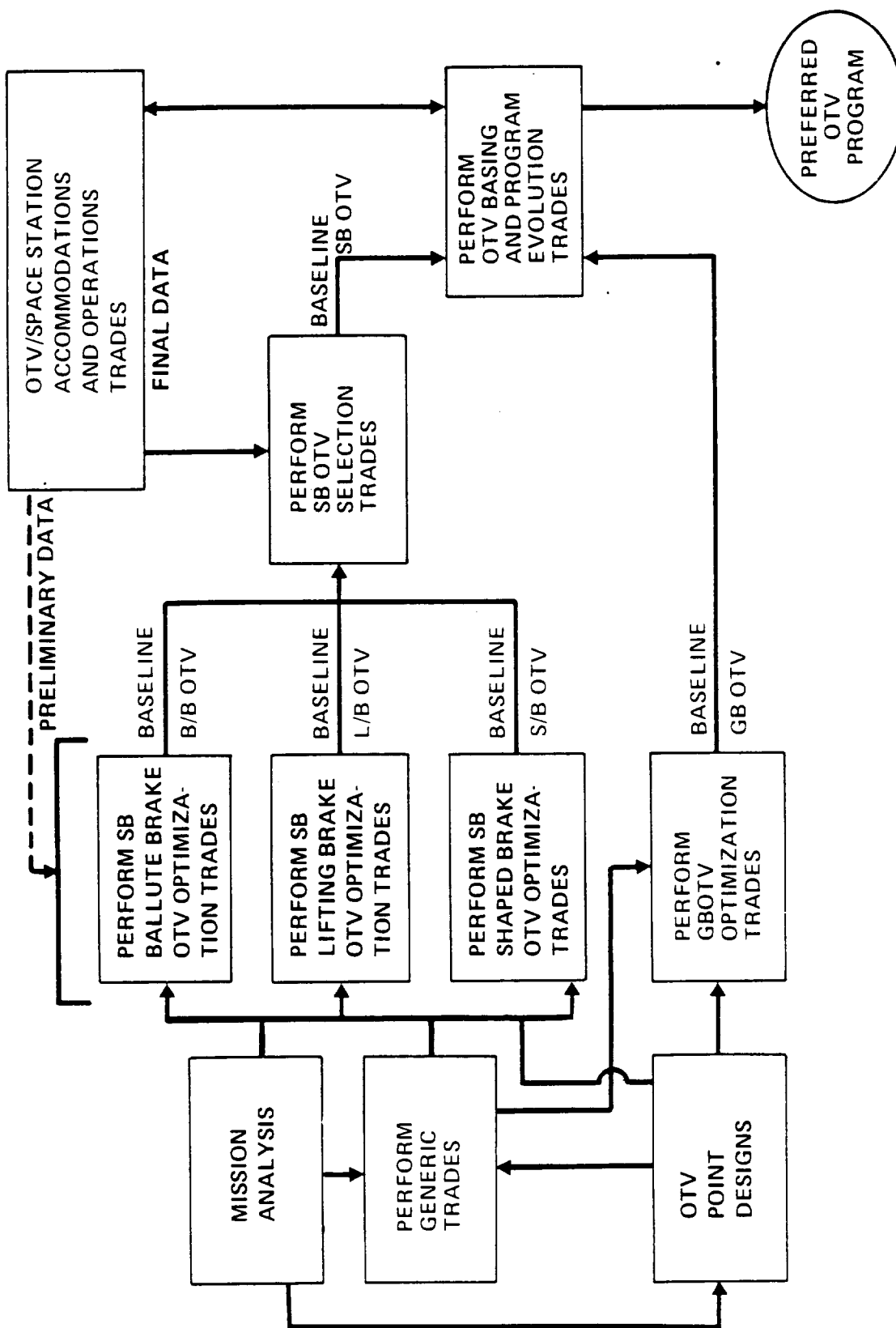
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Figure 2-1. Trade Study Logic Flow

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Table 2-1. Key Ground Rules

- FIGURE OF MERIT—COST IN 1985 DOLLARS
  - LIFE CYCLE—UNDISCOUNTED AND DISCOUNTED (10%)
  - TIME PHASED LIFE CYCLE COST (PAYBACK)
  - DDTE AND ANNUAL RATE DIFFERENCE
  - COST PER FLIGHT RELATIVE TO EXISTING SYSTEMS
- RECOMMENDATIONS BASED PRIMARILY ON LOW MISSION MODEL AND DISCOUNTING
- OTV MISSION MODELS (REV 8)
  - LOW   1994–2010   145 FLIGHTS (REDUCED 25% FROM MIDTERM)
  - NOMINAL   1994–2010   257 FLIGHTS
- SHUTTLE LIFT AND ORBITER CAPABILITY
  - PAYLOAD = 87,960–114 h (72,000 LBS @ 28.5°/140 NM)
- SHUTTLE COST PER FLIGHT
  - LOW MODEL $73 M (INCREASED 5% OVER MIDTERM)
  - NOMINAL MODEL $63.7M (NOT SPECIFIED AT MIDTERM)
- SCAVENGE PROPELLANT—LOW MODEL
  - 200,000 LBS PER YEAR @ $250 PER LBS
- IOC: GB OTV 1994;   SB OTV 1997

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Table 2-2 OTV Mission Model Composition Summary

1994 – 2010, REV. 8, 3-31-85

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PAYLOAD NO. SERIES	MISSION GROUP	WEIGHT (LB) UP/DOWN	LENGTH (FT)	MISSION MODEL		IOC LOW/NOM
				LOW	NOM	
13000	EXPERIMENTAL GEO PLATFORM	12000/0	30	1	1	2000/1995
13000	OPERATIONAL GEO PLATFORM	20000/0	35	5	6	2004/1998
13000	UNMANNED GEO PLAT. SERVICING	7000/4500	9	1	1	2001/1996
15000	MANNED GEO SORTIE	7500/7500	10	3	17	2008/2002
15000	GEO SERVICE STATION ELEMENTS	13000/0	15 – 20	2	2	2002/1998
15000	GEO SERVICE STA. LOGISTICS	12000/2000	15	5	26	2004/1998
17000	PLANETARY	2000–40000/0	5 – 35	6	14	1994/1994
17000	UNMANNED LUNAR	5000–20000/0	20	2	2	2007/2001
17000	MANNED LUNAR SORTIE	80,000/15,000	50	0	3	2015/2006
17000	LUNAR BASE ELEMENTS	80,000/0	53	0	3	2020/2008
17000	LUNAR BASE SORTIE/LOGISTICS	80,000/10,000	60	0	6	2021/2009
18000	MULTIPLE GEO PAYLOAD DELIVERY	12000/2000	25	46	79	1994/1994
18000	LARGE GEO SATELLITE DELIVERY	20000/0	20 – 35	3	7	2001/1997
19000	DOD (GENERIC)	12000 – 20000 (EQUIV.)		68	85	1994/1994
	SUBTOTALS			142	252	
10100	REFLIGHTS			3	5	1996/1997
	TOTALS			145	257	

Figure 2-2. OTV Sizing for Principal Missions

- VEHICLE SIZED FOR INDICATED MISSIONS
- SPACE BASED SINGLE STAGE, LO_2/LH_2
- 2 ADVANCED ENGINES, ϵ = 1000, HYDRAZINE RCS
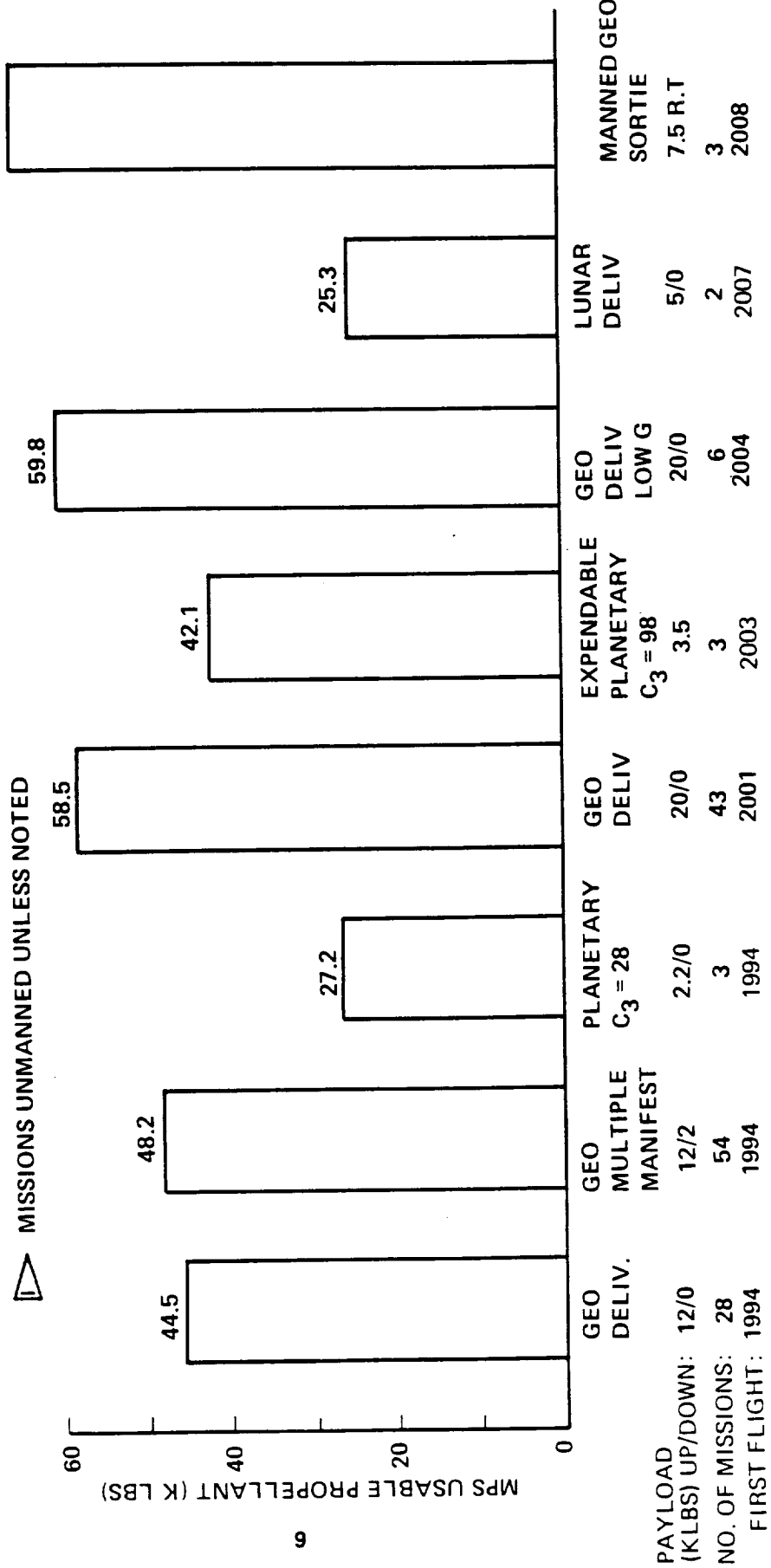- EXPENDABLE BALLUTE, TURNDOWN = 1.5, BACK WALL TEMP = 600°F

△ MISSIONS UNMANNED UNLESS NOTED

REV 7
16K — R.T.
R.T.

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65.2

	GEO DELIV.	GEO MULTIPLE MANIFEST	PLANETARY C_3 = 28	GEO DELIV	EXPENDABLE PLANETARY C_3 = 98	GEO DELIV LOW G	LUNAR DELIV	MANNED GEO SORTIE
PAYLOAD (KLBS) UP/DOWN:	12/0	12/2	2.2/0	20/0	3.5	20/0	5/0	7.5 R.T
NO. OF MISSIONS:	28	54	3	43	3	6	2	3
FIRST FLIGHT:	1994	1994	1994	2001	2003	2004	2007	2008

Bar values: 44.5, 48.2, 27.2, 58.5, 42.1, 59.8, 25.3, 65.2

MPS USABLE PROPELLANT (K LBS)

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should be noted that the propellant load for each mission is shown for the case of the vehicle being sized specifically for that mission. Also shown are other mission parameters such as payload, number of missions for each category and first flight date.

The manned GEO sortie mission was used for the sizing mission for the SBOTV trades up through vehicle optimization. This selection was used because even though there are only three of these missions, the propellant load is only slightly larger than that of the 20,000 lb GEO delivery missions. The final definition of the SB OTV however compared the single stage approach with sizing the main vehicle for propellant loads applicable to the 12,000 lb GEO delivery and GEO multimanifest missions and adding an auxiliary propellant tank for more demanding missions.

Payloads for the nominal model are the same in mass as for the low model with the exception that the lunar missions are significantly larger. For the 80,000/15,000 manned mission a total propellant loading of 180,000 lbs is required.

Further resolution on what was included in the life cycle cost analysis is indicated in figure 2-3 for those hardware elements and operations associated with the space transportation system involving the OTV. Particular emphasis was placed on defining the major parameter associated with the operations cost since this aspect contributes the majority of the LCC.
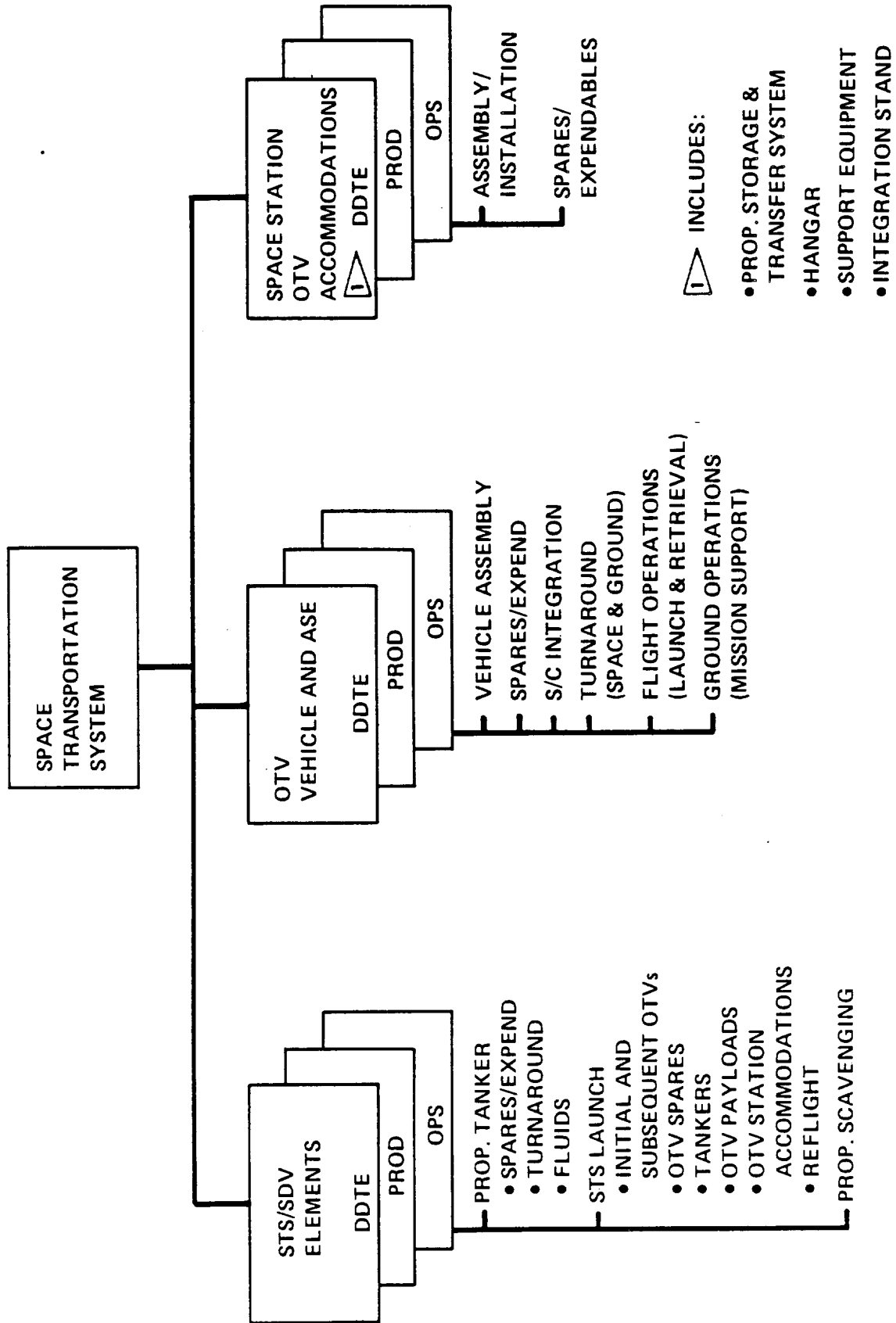
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Figure 2-3. OTV Related Cost Contributors

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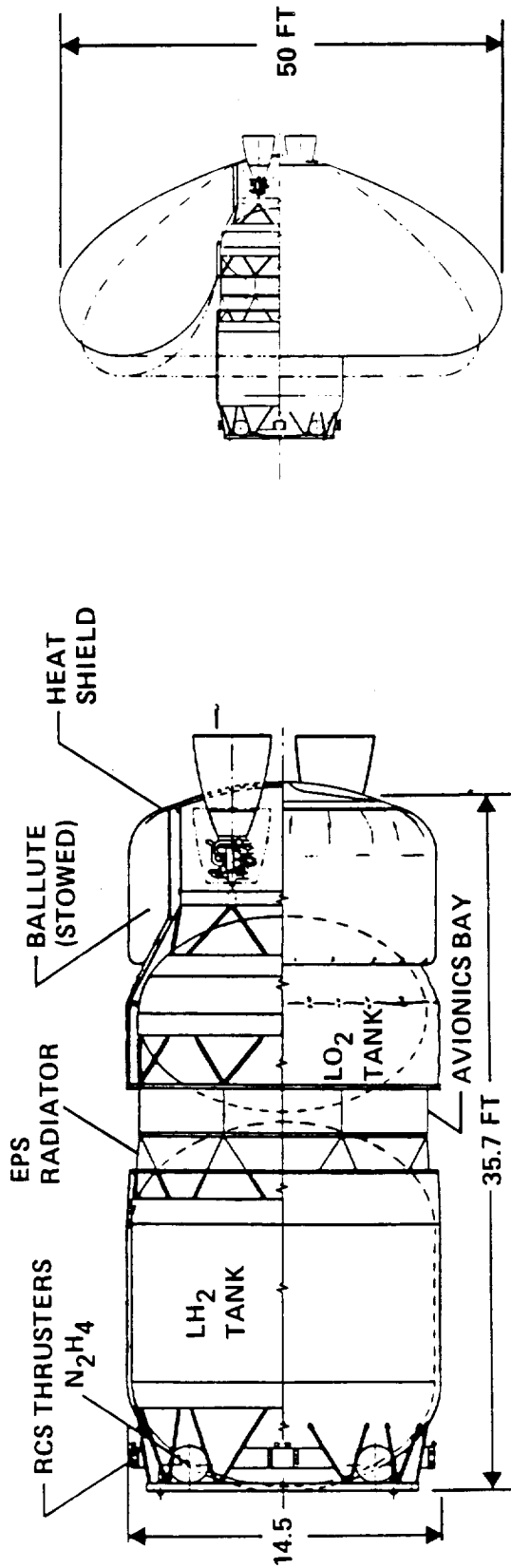
3.0 GENERIC TRADES

Several trades and analyses fall under the category of generic trades or those whose result is applicable to all OTV concepts. Specifically these trades included those associated with propulsion and operability. A ballute braked SB OTV was used to perform the trades however use of any one of the other SB OTV concepts would give the same results. Furthermore, to simplify the analysis and get though some of the basic trades as effectively as possible we used a single stage vehicle wherever practical. The first three years of the mission model was eliminated since the SB OTV's did not have an IOC until 1997. However, should the full model be used there would be no difference in the selected concepts.

3.1 REFERENCE CONFIGURATION

The characteristics of the SB OTV used to perform the generic trades as well as the optimization trades for the ballute brake OTV are shown in figure 3.1-1. The configuration is an updated version of the Phase I midterm concept primarily reflecting a better understanding of the concept in terms of design and operational features. A deployable debris shield was eliminated in favor of a fixed shield. The propellant tank was reduced 4 inches to have the total vehicle diameter to be compatible with the 180 in dynamic envelope of the Space Shuttle's Orbiter. RCS thrusters were moved from the mid body to the forward end to minimize plume impingement concerns on the radiators and ballute when it is deployed. The ballute when deployed is 50 ft in diameter, uses a turndown ratio of 1.5 and has a backwall temperature of 600°F and is used only once. During the aeromaneuver the engines are stowed within the heat shield. When sized for the manned sortie mssion the vehicle is 35.7 ft in length and has a startburn weight of 78,170 lbs.

Table 3.1-1 identifies a number of design and operational features that are common to all SB OTV's including the reference concept. In addition, the design features are also applicable to the GB OTV. One exception, is that the main engine for the GB OTV would not need the space maintainable features or diagnostic provisions. The remainder of the design features are self explanatory.

The other exception is that the SB OTV is always launched empty. This approach minimizes the structural weight and thus minimizes the amount of propellant per mission. The SB OTV is stored in a hanger for several reasons: (1) maintenance on the OTV can be more effectively performed and (2) protection is provided against space

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50 FT

HEAT
SHIELD

BALLUTE
(STOWED)

EPS
RADIATOR

RCS THRUSTERS
N₂H₄

LH₂
TANK

LO₂
TANK

AVIONICS BAY

35.7 FT

14.5

WEIGHT SUMMARY (LBS)

• DRY   10,420

• PROP. 66,680   ⚠ 1

• OTHER FLUIDS 1070

⚠ 1 SIZED BY MANNED
      GEO SORTIE

OTHER FEATURES

• ADV. SPACE ENGINE
  I_{SP} = 483.2 SEC

• T/D = 1.5

• B/W TEMP = 600°F

KEY CHANGES

• SIMPLIFIED BALLUTE/SUPPORT SHELL

• ELIMINATE DEPLOY. DEBRIS SHIELD

• REDUCED TANK DIAMETER

• INCORPORATE EPS RADIATOR

• MOVED RCS THRUSTERS FORWARD

• REDUCED BALLUTE B/W TEMPERATURE
  TO 600°

Figure 3.1-1. SB Ballute Brake OTV

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Table 3.1-1. Common SB OTV Features

DESIGN [1]

- ADVANCED SPACE ENGINE LO_2/LH_2; I_{SP} = 483 SEC.

- 6 DOF N_2H_4 RCS

- ADV. COMPOSITE BODY SHELL

- 2219-T87 ALUMINUM TANKAGE

- ALUM. BUMPER (16 MIL) WITH MLI FOR DEBRIS/METEOROID PROTECTION

- ADV. FUEL CELLS (LO_2/LH_2)

- MLI/COATINGS FOR THERMAL CONTROL

- ADVANCED AVIONICS
  - RIRU, STAR TRACKER, GPS
  - TDRS TRANSPONDER, RF AMP
  - DMU AND DATA BUS
  - BITE

OPERATIONS

- LAUNCH EMPTY TO STATION

- HOUSE IN HANGAR

- FULL SERVICING AT STATION MAINTENANCE AND REFUELING

- OTV/PAYLOAD MATING

- RETURN TO EARTH AT END OF USEFUL LIFE OR LOW PROBABILITY FAILURE

[1] ALSO APPLICABLE TO GB OTV

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debris and meteoroids. The SB OTV will remain on orbit until the end of its useful life or a very rare failure occurs that has not had on-orbit maintenance provisions provided.

3.2 MAIN PROPULSION

The principal main propulsion trades that influence the overall vehicle configuration and operations involves the propellant and engine selection.
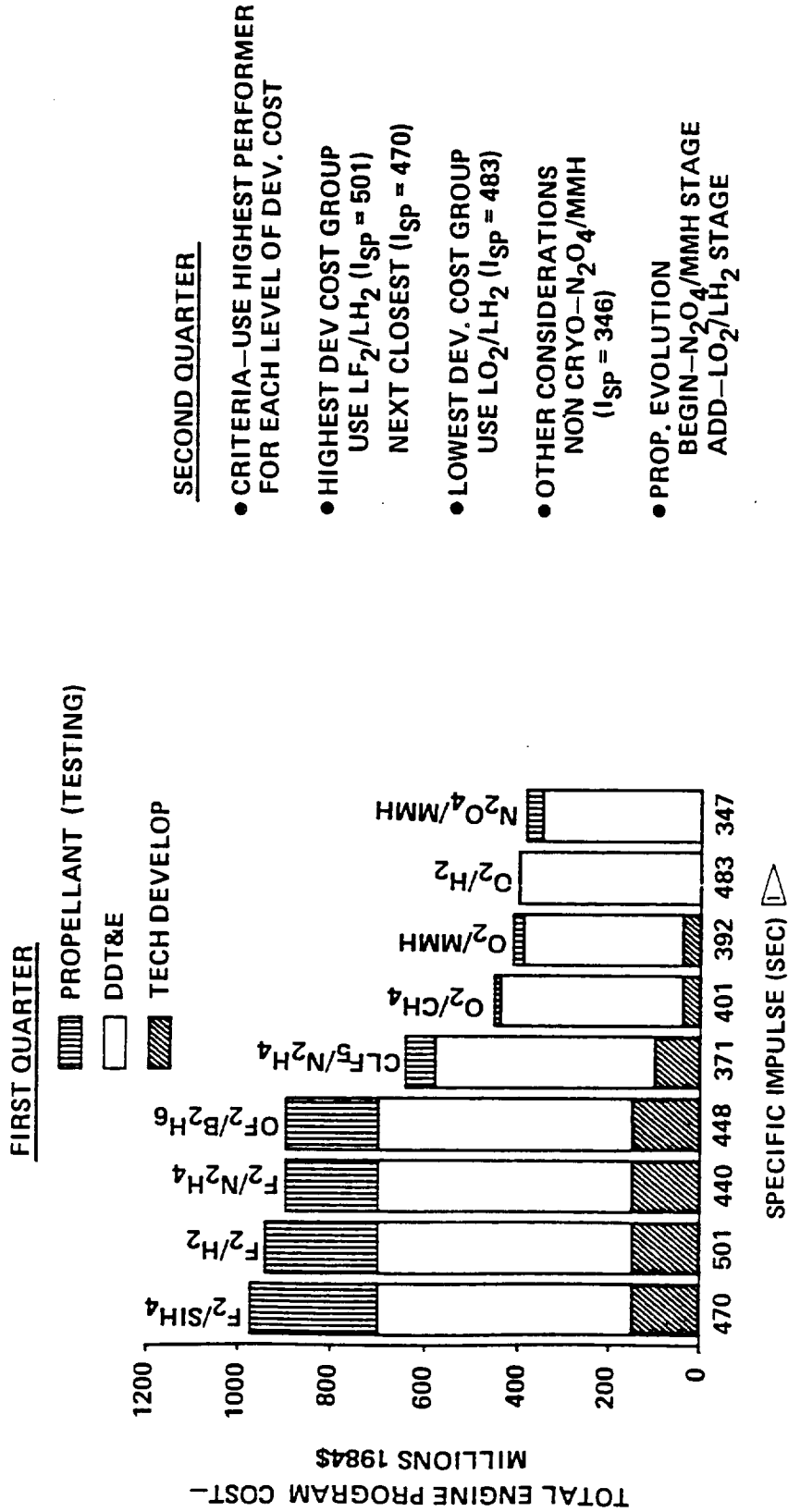
3.2.1 Main Propellant

This trade was conducted as part of the midterm effort and used the BAC version of the Rev. 7 nominal mission model. This version had 252 OTV flights (vs 450 for the NASA model) and turned out to be essentially the same as the NASA Rev 8 nominal model (257 flights). Although the Rev. 8 low model (145 flights) would have reduced the difference between the high and low performance concepts it was judged the conclusion would still be the same so the trade was not rerun. The other difference associated with the mid-term trade was that the weights of the vehicles were lower and should the higher final weights have been used the higher performance concepts would have again been more desirable. The remaining paragraphs of this section describe the trade as it was conducted.

Nine different propellant combinations were initially considered. The development cost characteristics for engines which use these propellants is shown in figure 3.2-1. There is essentially two groupings relative to cost. Applying screening criteria of selecting the highest performer (I_{sp}) from each group of development cost in addition to a non cryo propellant and a propellant suitable for system evolution resulted in selecting LF_2/LH_2, LO_2/LH_2, N_2O_4/MMH and $N_2O_4/MMH + LO_2/LH_2$ for further examination.

The configuration and performance characteristics for OTV's using the four candidate propellants are presented in figure 3.2-2. Specific impulse and bulk density contribute to the dry weight which in turn influences the propellant requirement. Based on these factors the LF_2/LH_2 systems require the least propellant followed by LO_2/LH_2. The storable system even using two stages required nearly twice the propellant as the LO_2/LH_2 system. The hybrid system provided an improvement over the storable but still required considerably more propellant than the all cryo systems.

The undiscounted and discounted life cycle cost (LCC) comparison of OTV programs using the candidate propellants is shown in figure 3.2-3. All hardware and operations elements identified in Section 2.0 are included. The N_2O_4/MMH system has the least development cost but its high operations cost associated with propellant delivery (due to low I_{sp}) resulted in the highest LCC. A LO_2/LH_2 system gives the least LCC if

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Figure 3.2-1 OTV Propellant Candidates

● SECOND QUARTER TRADE

PROPELLANT	I_{SP} [1] (SEC)	OTV DRY WEIGHT (LB)	PROPELLANT WEIGHT (LB)
SINGLE STAGE LO_2/LH_2	483	8560	61,075
SINGLE STAGE LF_2/LH_2	501	7700	54,400
TWO STAGE N_2O_4/MMH	346	15000 (7780) (7220)	114,400 (61,200) (53,200)
TWO STAGE LO_2/LH_2 N_2O_4/MMH	483 346	14990 (7910) (7080)	90,980 (44,230) (46,760)

[1] ALL ENGINES P_C = 1500 PSIA, ϵ = 1000

[2] SIZED FOR MANNED GEO SORTIE

32 FT
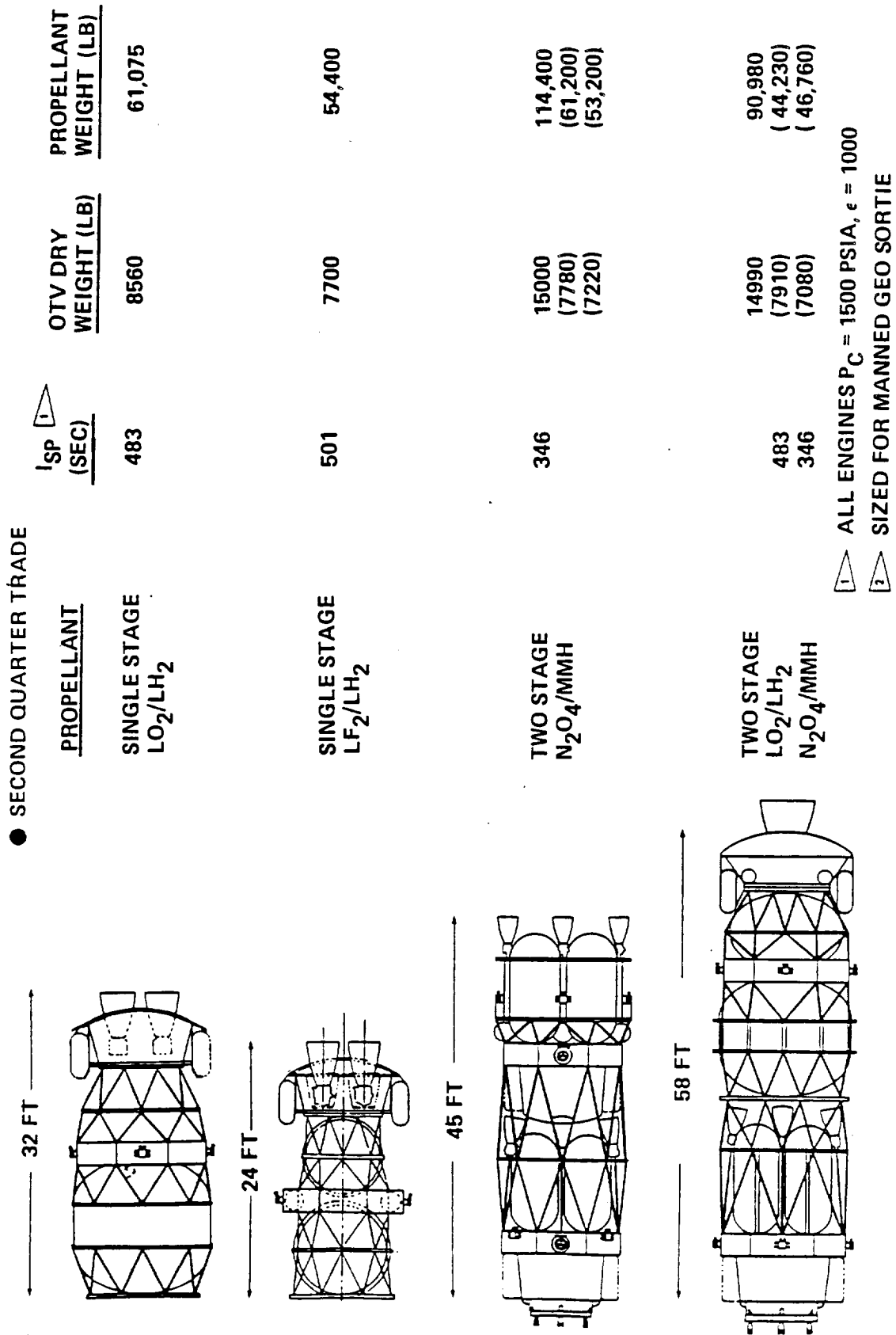
24 FT

45 FT

58 FT

Figure 3.2.2 Main Propellant Influence on OTV Configuration
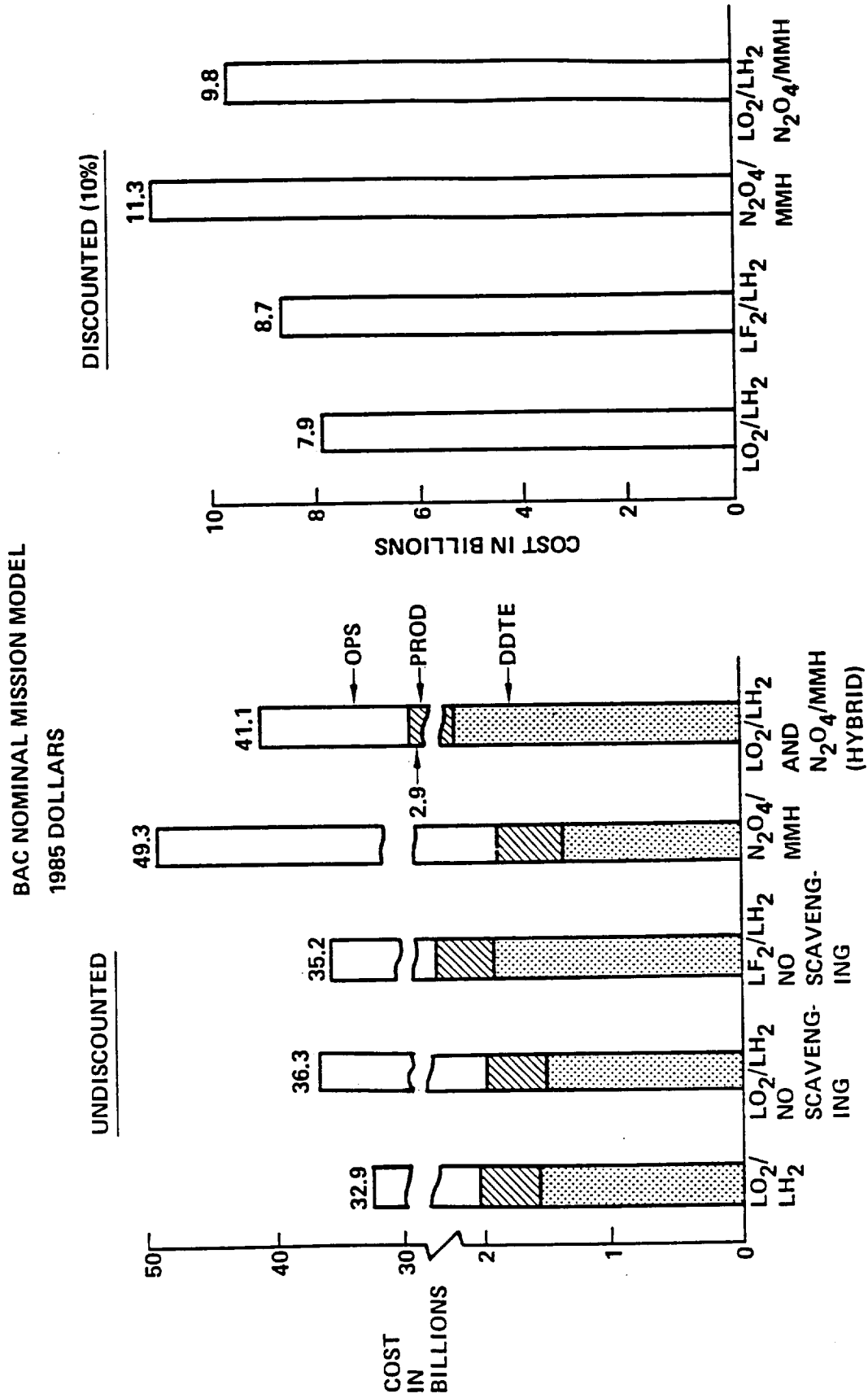
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Figure 3.2-3 Main Propellant Influence on OTV Program LCC

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propellant scavenging is used even though its performance is not as good as LF$_2$/LH$_2$. This occurs because over 30% of the propellant is delivered via scavenging which reduces the net propellant delivery cost by 30% relative to a system that does not use scavenging. Although LH$_2$ could be scavenged for the LF$_2$/LH$_2$ option it represents only a small fraction of the total propellant requirement and was judged not worth the complexity. The hybrid system had even a higher development cost than the LF$_2$/LH$_2$ system primarily because two stages rather than one required development.

Our recommendation for main propellant is LO$_2$/LH$_2$. This system provides a discounted life cycle cost advantage of 9% over the LF$_2$/LH$_2$ when propellant scavenging is used. In addition, the LO$_2$/LH$_2$ does not have the risks associated with handling and the extra equipment and operational procedures associated with LF$_2$. The recommended LO$_2$/LH$_2$ system provides a 30% LCC advantage over the storable system due to the differences in operations cost resulting form its performance characteristics. For performance reasons the storable system required use of two stages and this would also be additional operational complexity relative to the one stage LO$_2$/LH$_2$ system.

3.2.2 Main Engine

One of the top level trades associated with the study is that of selecting the main engine that can be used with the previously selected LO$_2$/LH$_2$ propellant. The key characteristics of the investigated engines are shown in table 3.2-1. Data for the advanced engine shows several parameters with different values for the space and ground versions of the engine. The most significant differences between engine candidates involve weight (value shown is for one engine and two is the baseline), I$_{sp}$ particularly for low g applications, life, and development time and cost. The key issue in this trade was whether the benefits of the advanced engine can offset its higher development cost. Hereafter, the advanced engine is referred to as ASE for advanced space engine even though some of its characteristics are different from another engine studied by NASA with the same name.

Propellant requirement and payload capability for OTV's using the candidate engines is presented in figure 3.2-4. For the case of performing the manned GEO servicing sortie (MGSS) mission, the ASE provides an 8.6% and 14% advantage over the RL10-III and RL10-IIB, respectively. Using a fixed amount of usable propellant for a GEO payload delivery mission, the ASE provides a 16.2% and 29% advantage over the RL10-III and RL10-IIB, respectively. In both cases, the higher I$_{sp}$ and lower weight per engine are the major contributing factors.

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Table 3.2-1 LO2/LH2 Main Engine Candidates

PARAMETER	OPTIONS		
	RL 10-IIB	RL 10-III	ADVANCED [1]
• WEIGHT (LBS)	392	380	200
• THRUST (LB$_F$)	15,000	7,500	5000
• I$_{SP}$ (SEC)	460	470	483
• LOW G TRANSFER I$_{SP}$ (1 ENGINE OPERATING)	445	458	481
• LIFE (HOURS)	5	5	10
(FLIGHTS)	10	10	20
• DEVELOPMENT TIME (YRS)	3	3	6 (5)
• DDTE COST ($M)	98	104	350 (300)
• UNIT COST ($M)	1.9	2.0	3
• PROP LOAD [2]	75.8	71.3	65.2

[1] COMMON FOR SB AND GB OTV'S EXCEPT THOSE IN PARENTHESIS (UNIQUE TO GB)

[2] FOR MANNED SORTIE MISSION

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GEO DELIVERY PAYLOAD CAPABILITY
USABLE PROP. = 65.2 LB

PAYLOAD CAPABILITY (1000's LBS)

20 — RL10-II (2) — 15.5
15 — RL10-III (2) — 17.2
ASE (2) — 20

PROPELLANT REQUIRED
MGSS
7.5K ROUNDTRIP

USABLE MAIN PROPELLANT (1000's LBS)

RL10-II (2) — 75.8
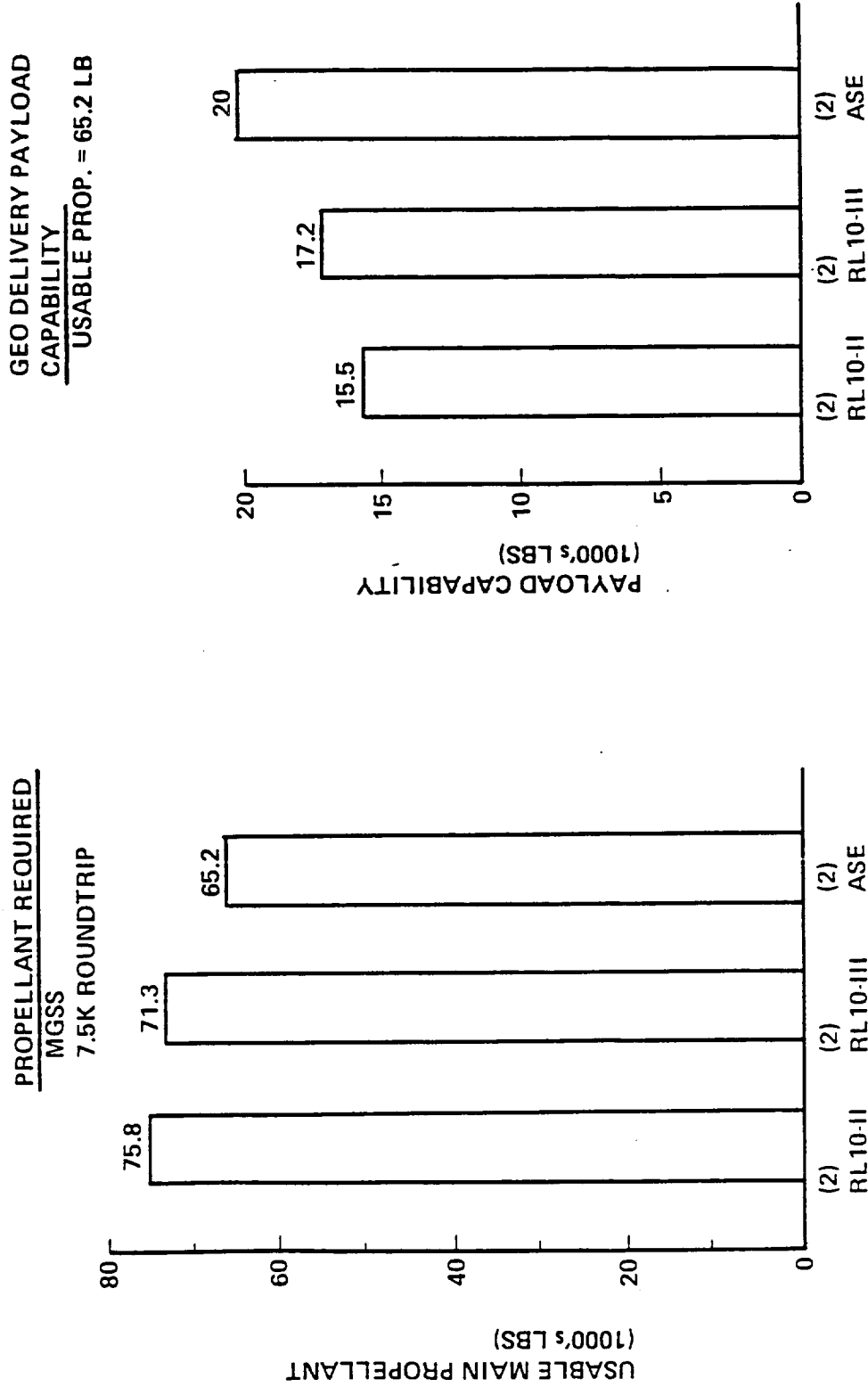RL10-III (2) — 71.3
ASE (2) — 65.2

Figure 3.2-4 OTV Performance Comparison of LO_2/LH_2 Engine Candidates

The undiscounted and discounted life cycle cost (LCC) comparison of the main engines are presented in figure 3.2-5 in terms of their influence on total OTV program cost. An OTV with ASE's provides a 4.4% and 8.4% advantage over the RL10-III and RL10-IIB respectively. However, the ASE does have higher development cost and thus the discounted LCC comparison is closer which makes the time phased cost comparison an important parameter.

The plots shown in figure 3.2-6 present the cumulative LCC difference by year between a reference vehicle and any alternate vehicle in both discounted and undiscounted dollars. The influence of discounting in terms of how soon a given option begins to payback is clearly indicated. The reference vehicle has been chosen as one which uses ASE'S and as such is indicated by the zero dollar line. For the discounted case, which is most significant in terms of decisions when considering advanced hardware/programs, the data indicates the reference vehicle using ASE is increasingly more expensive than the alternatives out to the point of beginning to fly the missions in 1994. In subsequent years however, the ASE is more efficient in terms of performance and requires less propellant thus lower recurring cost. By about 2001 the reference OTV with ASE's becomes cheaper than an RL10-11B OTV and cheaper than an OTV with RL10-111 in 2005.

Our recommendations for main engine for OTV application is the advanced LO_2/LH_2 system with the characteristics indicated in table 3.2-2. Although the discounted payback relative to the closest competitor (RL10-111) takes a little longer than desired, other advantages such as additional performance capability to handle changes in mission requirements and better operations features in terms of dealing with design life and maintenance justify the selection of the ASE.

Application for a GB OTV has not been shown; however, the performance aspects are even more important due to liftoff limits as will be discussed later in section 5.0.

3.3 OPERABILITY

Several issues relate to the overall operability of the OTV. These include: (1) what is the optimum amount of redundancy associated with a given mission, (2) which components should have the potential for on-orbit maintenance, and (3) how is man rating best achieved. Each of these issues is discussed in terms of trades and analysis in the following paragraphs.
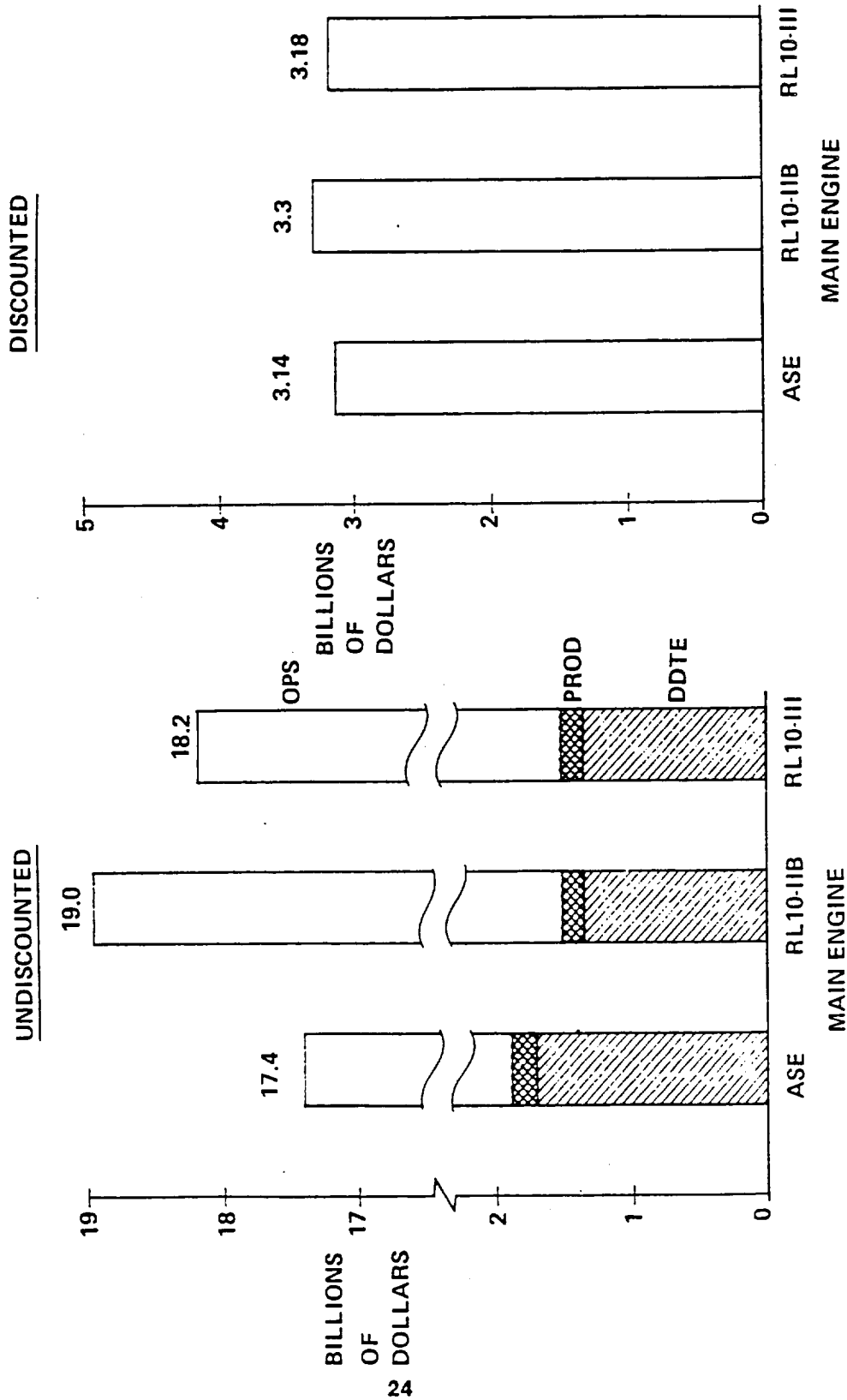
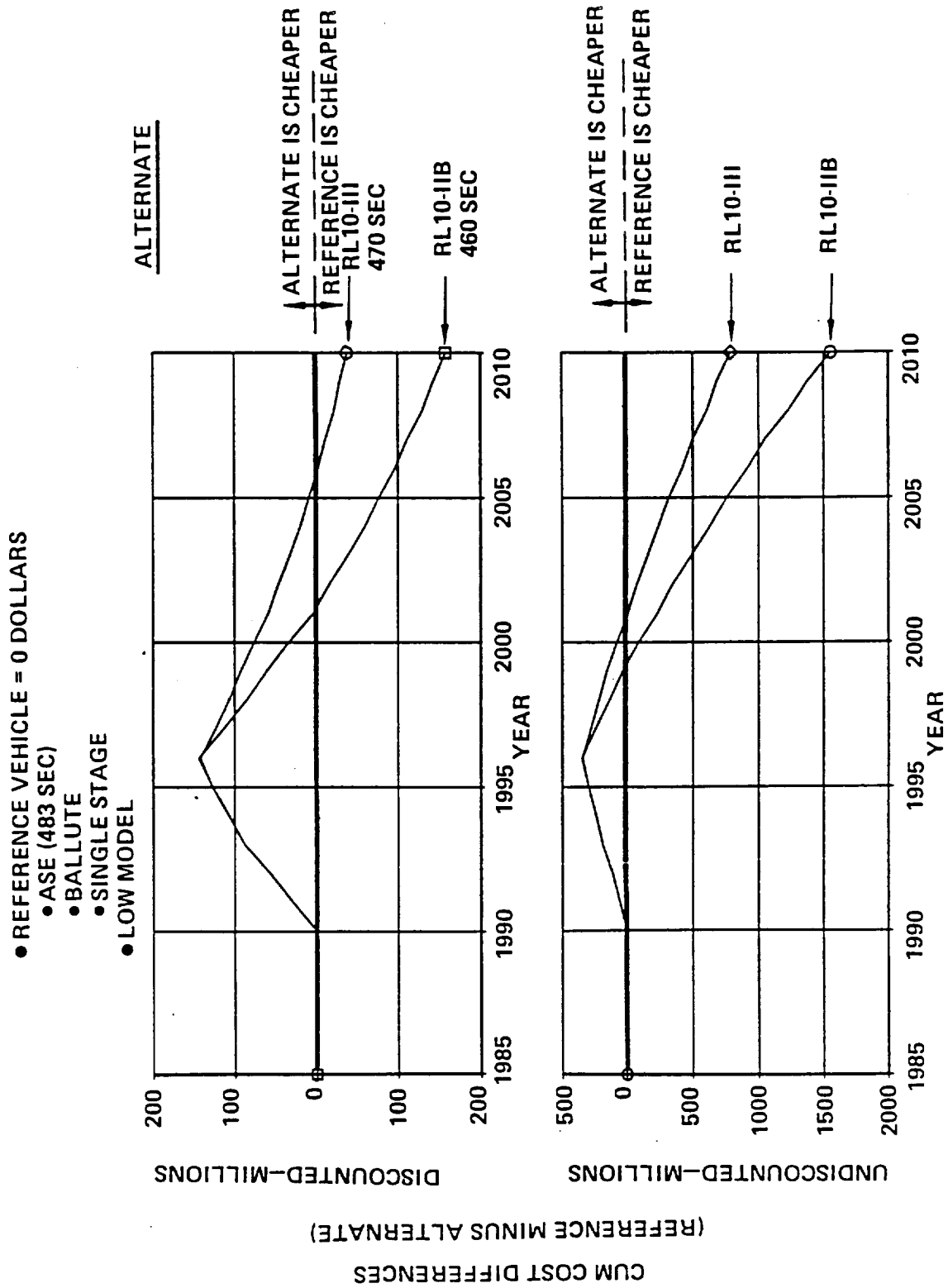Figure 3.2-5 Main Engine Influence on OTV Program LCC

Figure 3.2.6 OTV Time Phased LCC Comparison Main Engine Trade

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Table 3.2-2. Main Engine Assessment

● RECOMMENDATIONS—ADVANCED ENGINE

THRUST = 5000 LB$_F$

P_c = 1500 PSIA

EXP RATIO = 1000

● LCC (UNDISCOUNTED) SAVINGS OF 4.4% AND 8.4% VERSUS RL10IIB AND -III

● PAYBACK (DISCOUNTED) WITHIN 7 YEARS AFTER IOC (LOW MODEL) RELATIVE TO RL10-IIB

● PERFORMANCE AND OPERATIONAL CHARACTERISTICS RESULT IN LESS SYSTEM IMPACT FOR CHANGES IN REQUIREMENTS

● PERFORMANCE BENEFIT EVEN MORE SIGNIFICANT FOR GB OTV APPLICATION

3.3.1 Redundancy Optimization

In the area of redundancy optimization the effort was focused on unmanned vehicles since the low model was dominated by unmanned missions (97%). The method employed to determine the optimum redundancy was to find the reliability (meaning complement of components) value which gave the least program cost. Four cost factors are involved. Higher reliability means more components and increased weight which would increase the development, production and operations (that portion dealing with propellant launch) costs. However, one cost factor, reflight cost relating to having to refly due to a failed mission, would decrease with increased reliability.

Increases in reliability were determined by adding components to a single thread (one component per required function) that contribute the most delta reliability per delta pound or delta unit cost. The results of this step in the analysis is shown in figure 3.3-1 including an indication of a few of the key components. A more indepth analysis of the reliability prediction both for the single thread point and increases in reliability with additional components can be found in Volume II, Book 3.

The cost impact on DDTE, production and operations cost when going from the single thread reliability point of 0.92 to a vehicle reliability level of 0.9998 (highest value calculated) is shown in figure 3.3-2. A major contributor to the increase in DDTE cost is that associated with software (30%) necessary to manage the additional components. Production cost is reflecting the additional components necessary for the equivalent of 2.5 vehicles which would be required to perform 100 flights. The extra component weight requires more propellant per flight and thus increased launch cost. It will be noted however the greatest swing in cost in going from the single thread point to 0.9998 is that associated with reflight. This curve reflects the contributions occurring if the flight is lost on the delivery leg (prior to payload deployment) or on the return leg. The primary cost difference between the delivery and return leg is that if failure occurs during the former, a replacement spacecraft must be bought ($100M) and the OTV and its propellant for the reflight must be launched whereas for the downleg only a new OTV needs to be procured.

The combined effect of all of these cost factors is shown in figure 3.3-3 and indicates a cost optimum reliability of 0.995. A few of the more significant components contributing to the optimum redundancy are indicated. Noteworthy is the addition of a second main engine. The cost optimum reliability point required the addition of 45 components to a single thread design which is significantly less than having a full fail safe (one complete extra set of components) configuration. A fail safe concept would
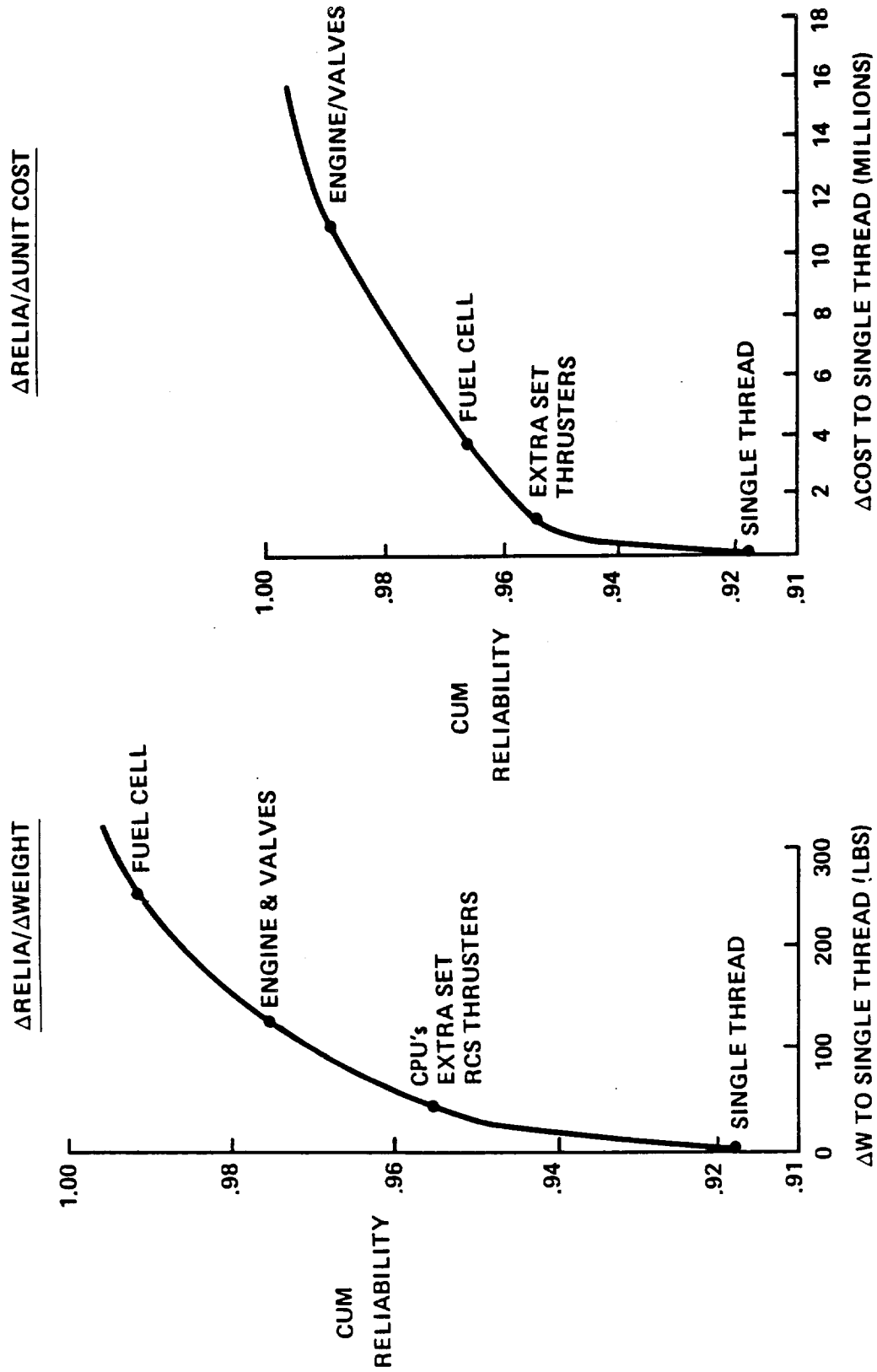
27

Figure 3.3-1. Optimized Addition of Redundant Components
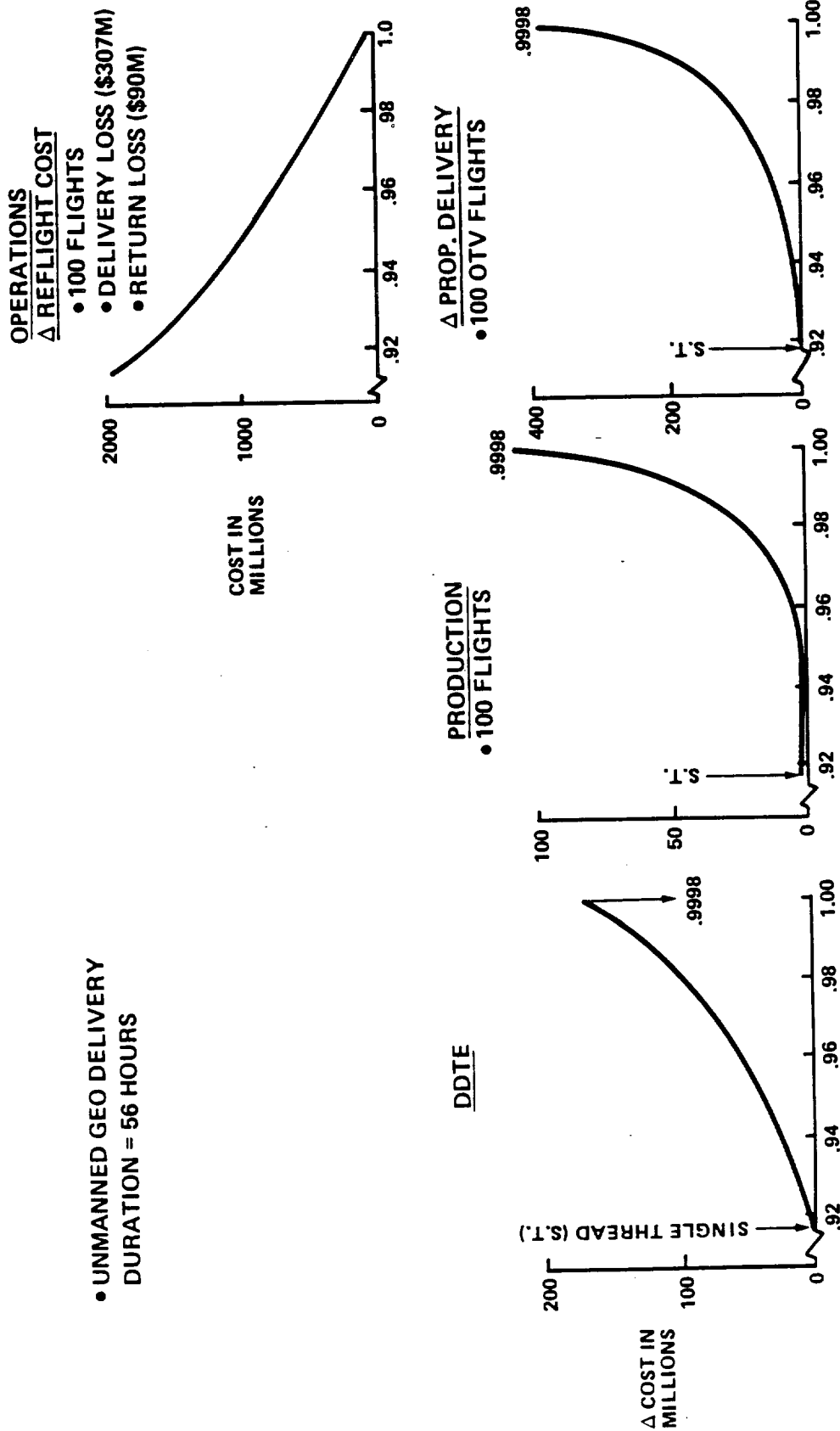
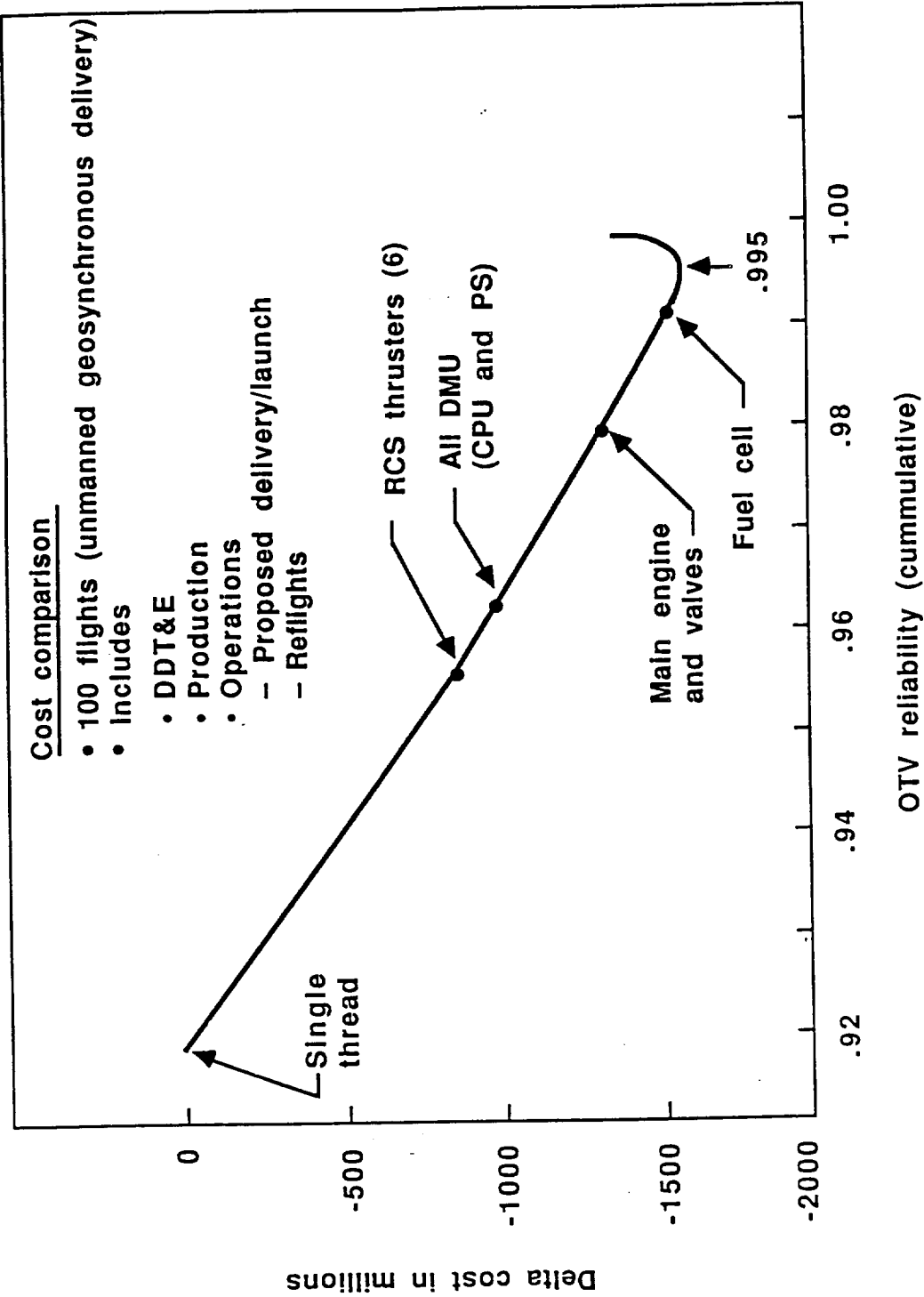OTV-336

Figure 3.3-2. Cost Sensitivity to Reliability

Figure 3.3.3. Cost Optimum Redundancy

OTV-223

require an extra 1000 pounds of propellant per mission and result in a $2 million dollar penalty for each flight.

Sensitivity of the optimum reliability level to spacecraft and launch cost for unmanned applications was also investigated. The prior analysis had assumed $70M for the STS launch cost and $100M for the spacecraft cost. The cost optimized reliability was .995. For the cases of changing only the spacecraft cost to $300 or changing both spacecraft and launch cost to $300M and $100M respectively, there was no impact on the cost optimum point. However, changing only the launch cost to $100M moved the cost optimum reliability point back to 0.992.

3.3.2 On-Orbit Maintenance Provisions

An additional aspect of orbital operations associated with a SB OTV is that of identifying how many of the components required for redundancy reasons should also have "easy" on-orbit remove and replacement (R&R) provisions. By easy is meant performing the R&R task while in a pressure suit and zero g or even via robotics. For example, component installation characteristics on most current spacecraft or space transportation systems generally use an approach that is earth oriented and would be extremely difficult if not impossible to effectively R&R a component in space. Past studies such as Future Orbital Transfer Vehicle have indicated a 25% weight penalty (average) to enable effective on-orbit R&R. Should the component not be designed for effective R&R, the SB OTV may have to be returned to earth for these repairs.

The first step in this analysis was to identify the components with the most frequent failure and impact on frequency of OTV earth return for maintenance. This data is presented in table 3.3-1. The information on the left side lists the components with the most frequent failures taking into account the failure rate of the component and the number of components on-board a fail safe reliability configuration. For example a main engine is expected to fail every 27 flights. The cum for the total vehicle is about one failure per 6 flights.

Should no on-orbit R&R provisions be provided, data on the right side indicates the SB OTV would be brought back to earth for maintenance on the average of every six flights which would dramatically decrease the effectiveness of a spaced based OTV. However, incorporating the on-orbit R&R capability improves the MMTER considerably. For example, capability to R&R the RCS thrusters increases the MMTER to once every 11 flights. Also incorporating provisions for the main engine increases the cum MMTER to nearly one every 19 flights etc.

Table 3.3-1. Component Maintenance Characteristics

- UNMANNED GEO DELIVERY (T = 56 HOURS)
- FAIL SAFE CONFIGURATION

MOST FREQUENT FAILURE	
COMPONENT	MMTR [1] (INDIVIDUAL)
RCS THRUSTER PAIR	13.1
MAIN ENGINE	26.9
FUEL CELL	41.4
CPU & POWER SUPPLY	117.5
MEMORY CARDS	297
GYROS	414
AMUX/ADC	465
SER/DIG I/O	938
BUFFER I/O	1072
GPS RECEIVER	1254

CUM TOTAL VEHICLE = 6.0

MEAN MISSIONS TO EARTH RETURN	
CUM ON-ORBIT MAINTENANCE PROVISIONS	MMTER [2]
NONE	6.0
RCS THRUSTERS	11.0
MAIN ENGINE	18.6
FUEL CELL	33.9
CPU & POWER SUPPLY	47.5
MEMORY CARDS	56.6
GYROS	65.6
AMUX/DIG I/O	83.1
BUFFER I/O	90
GPS RECEIVER	97

[1] MEAN MISSIONS TO REPAIR

[2] MEAN MISSIONS TO EARTH RETURN

The impact of providing easy on-orbit R&R can be expressed in several ways as shown in figure 3.3-4. On the left is shown the impact on reducing the number of relaunches as the MMTER is increased. However, as indicated earlier to achieve the easy on-orbit R&R requires additional weight in the form of simplier but heavier mounting plates and fastners and quick disconnects on fluid and electrical connections. The impact of higher MMTER on weight is shown on the right plot. In addition to the dry weights of the components, the resulting propellant increase is also indicated.

The cost optimum amount of maintenance provisions is found by combining the relaunch and per flight cost as shown in figure 3.3-5. As would be expected, a higher MMTER results in less cost associated with relaunches but increased cost for launching extra propellant due to heavier weight. As indicated, the influence of relaunches is much more significant and results in the cum cost curve becoming rather shallow after a MMTER of 60 flights is reached.

Several observations can be made from these data. Although the cost does get lower with MMTER greater than 80 flights, provisions for easy R&R of components contributing more to the MMTER may not be justified. Second, the rather arbitrarily assumed design life of 40 flights for the OTV turned out to be quite reasonable in terms of impact of on-orbit maintenance provisions. This design life should include the maintenance capability at least up through fuel cells but beyond this point the payoff is not that significant. However, it should be noted that additional design life say to 60 flights could reduce the OTV production quantity by one vehicle in 124 flights and thus save approximately $50 million in production cost as well as reducing operations cost associated with on-orbit maintenance by another $30 million if the additional capability is provided.
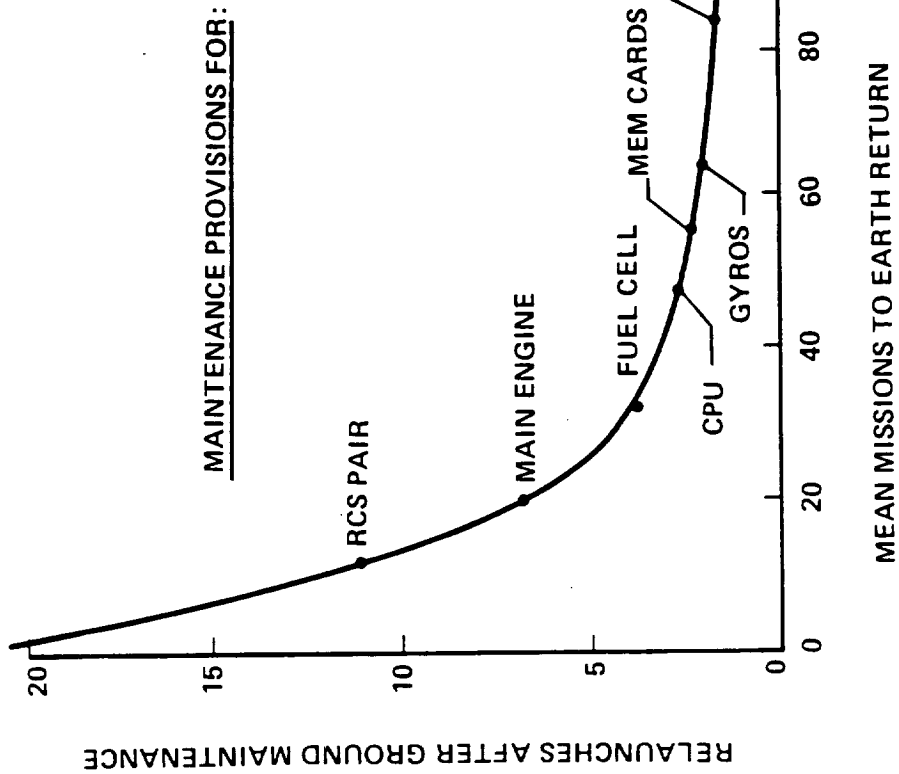
3.3.3 Man-Rating

Safety considerations associated with manned OTV flights, the weight of the additional components and the flight time and frequency make the most effective method of achieving man rating a challenging issue. In the low mission model the first flight does not occur until 2008 followed by one each in 2009 and 2010.

Several options for satisfying the manned OTV flights were considered and are summarized in table 3.3-2. Option 1 had full man-rated capability beginning with the IOC and as a result the additional weight would have a significant impact on LCC but low development cost. This option was used for all SB OTV trades out through selection of the preferred SB OTV concept because it simplified the analysis and our primary goal through that point was to have good relative comparisons. Option 2 in effect had a

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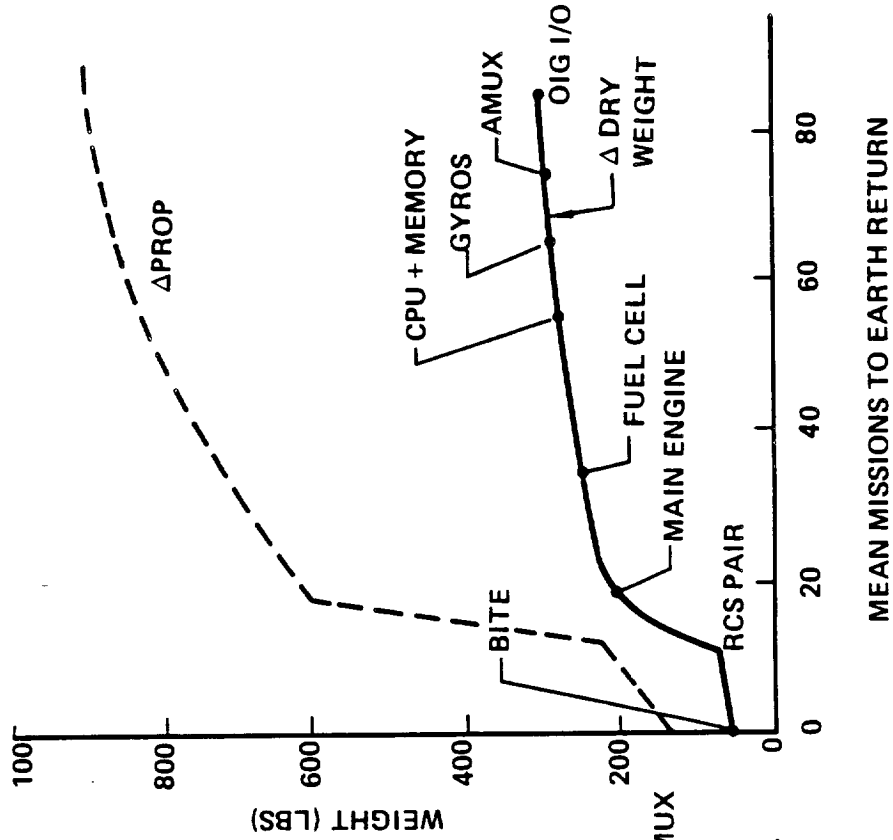OTV-848

• 124 FLIGHTS

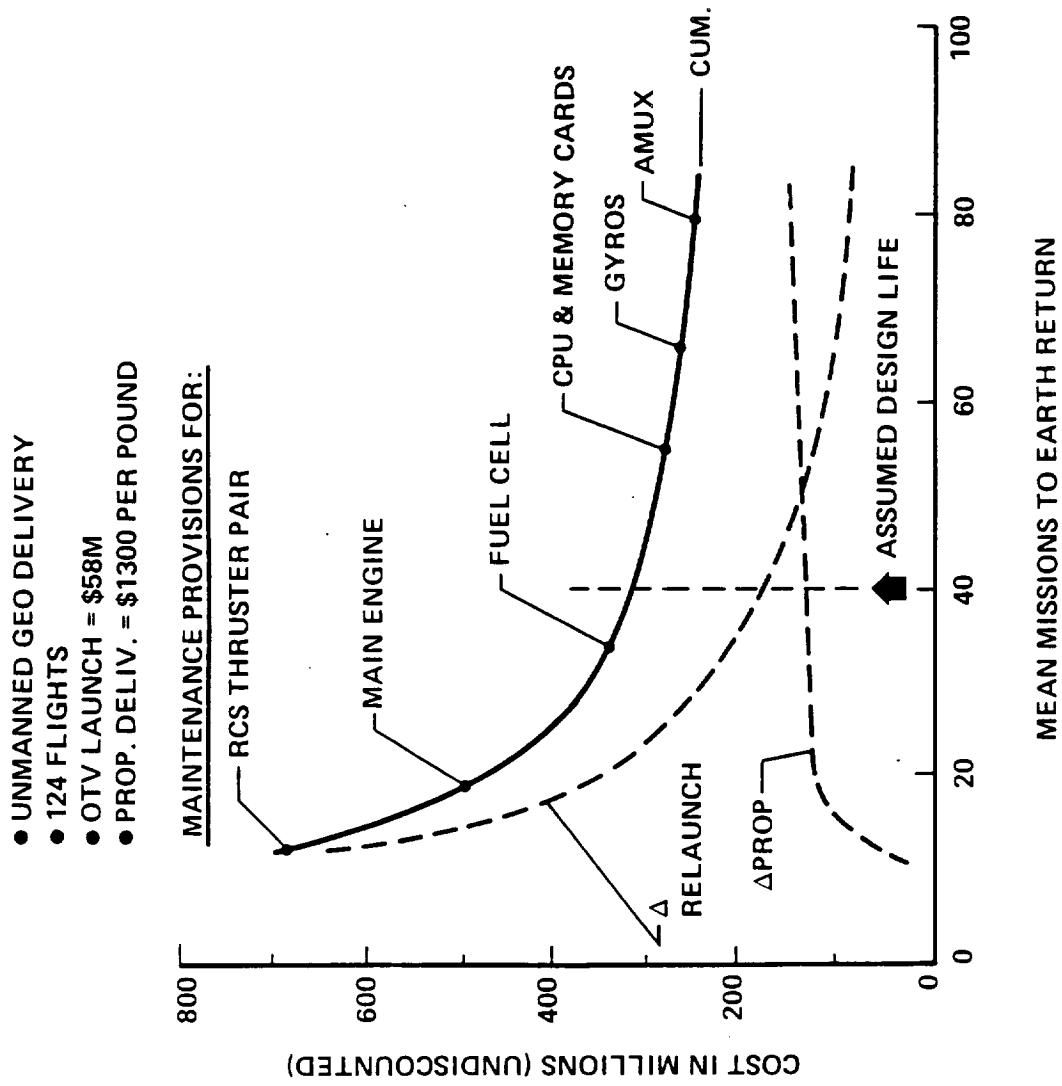Figure 3.3-4. Maintenance Provision Impact

OTV-846

Figure 3.3-5. Cost Optimum Maintenance Provision

OTV-746

Table 3.3-2.   Man Rating

KEY GROUND RULES

- ONLY 3 MANNED MISSIONS—FIRST FLIGHT IN 2008 (LOW MODEL)
- DUAL FAILURE TOLERANT

OPTIONS	CHARACTERISTICS	ASSESSMENT
1. ONE VEHICLE/FULL CAPABILITY	• CONFIGURE FOR MANNED MISSION AT IOC	• USED TO PERFORM BASELINE SELECTIONS • LOW DEV. COST • HIGHEST LCC IMPACT
2. TWO VEHICLES	• ONE FOR UNMANNED FLIGHTS— COST OPTIMUM • ONE FOR MANNED FLIGHTS	• HIGHEST DEV. COST • POOR UTILIZATION OF 2ND VEHICLE
3. ONE VEHICLE/ REDUNDANCY IN CREW MODULE	• OTV HAS COST OPTIMUM EQUIP- MENT AND MANNED SCAR • REDUNDANCY IN CREW MODULE	• INTERFACE MORE COMPLEX AND HEAVIER
4. ONE VEHICLE/FULL POTENTIAL	• SIZE OTV FOR ALL NECESSARY SYSTEMS • UNMANNED FLIGHTS CARRY MANNED SCAR • MANNED FLIGHTS HAVE COM- PONENTS ADDED/REMOVED	• SELECTED • BEST COMPROMISE OF VEHICLE UTILIZATION, PERFORMANCE AND COST • SAVES 227 LBS OF EQUIPMENT WHICH SAVES > $110M

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tailored vehicle for manned application which would add to the DDT&E and if this vehicle was used for unmanned flights it would pay a performance penalty. The third option had some of the redundancy for a manned OTV placed on the vehicle (thrusters, wiring, plumbing) but wherever practical the remainder was placed in the crew module. Although this minimized the performance penalty for other missions it did complicate the interface between the two OTV elements. The fourth option was that of incorporating into one vehicle design the full potential for manned flights. This consisted of having the necessary volume, plumbing, wiring, data cables installed in the basic unmanned OTV. On a manned mission the required "functional boxes" (i.e. fuel cell) were installed before the flight. After the flight these functional boxes were removed.

A complete cost comparison of these options was not conducted. Option 4 (one vehicle/full potential) was selected and used to perform the trades dealing with selection of the preferred SB OTV and basing mode. Although this option may not be as cost effective as Option 2 for the Rev. 8 mission model it does provide a high degree of flexibility to perform the manned mission should it occur sooner than indicated. In addition, it is more cost effective than Option 1 as will be discussed in the next paragraph and has far less operational complexity than Option 3. It is suggested that any further analysis in this area should consider variants of the Rev 8 model in terms of the number, frequency and IOC of manned missions.

The weight implications of man rating options relative to the cost optimum redundancy used for the unmanned OTV is indicated in table 3.3-3. To achieve full man rated capability an additional 83 components were required resulting in an increase of 418 lbs relative to the cost optimum unmanned OTV. Incorporation of only the manned scar provisions (option 4 in the previous paragraphs) into the unmanned vehicle would reduce this weight impact to 191 lbs. The result of using the manned scar approach is a savings of 227 lbs of equipment which translates into 680 lbs of propellant per flight and nearly $110 million savings over the 124 flight mission model.

Table 3.3-3. Component Comparison Cost Optimum Versus Man Rated

SUBSYSTEM	Δ FOR MAN RATED		MANNED SCAR WEIGHT
	COMPONENTS EFFECTED	WEIGHT	
● AVIONICS			
● GNC	1	20	0
● COMMUNICATIONS	6	40	7
● DATA HAND.	27	49	22
● ELECTRICAL			
● SOURCE	10	115	10
● CONV./DIST.	1	40	20
● THERM. CONTROL	2	13	13
● RCS			
THRUSTERS	8	22	0
MANIFOLD	4	6	6
● MPS			
● FEED/DUMP	4	25	25
● PRESSURIZATION	8	24	24
● VENT/RELIEF	12	64	64
	83	418 LBS	191 LBS

1▷ ENVELOPE, PLUMBING, WIRING, CABLING

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4.0 SB OTV OPTIMIZATION TRADES

This section presents the trades associated with the individual optimization of the ballute brake, lifting brake, and shaped brake configurations and concludes with the trades performed to select the preferred aeroassist concept and staging approach. Further discussion concerning the various concepts investigated can be found in Volume II, Book 3.

4.1 BALLUTE BRAKED OTV

Trades conducted to establish the overall configuration, performance and cost characteristics include turndown ratio, backwall temperature and drag control mode.

4.1.1 Turndown Ratio

The turndown ratio (TR) for the ballute is defined as the maximum to minimum value on C_DA during the aerobraking maneuver. Changing the TR during the maneuver is one means to counter the uncertainties in the predicted atmosphere, errors in guidance and navigation, etc. The factors associated with the TR trade are shown in figure 4.1-1. The TR's considered resulted in a range of apogee velocity corrections. Several key issues have been associated with turndown. Obviously the impact of the delta V after the maneuver is of interest, but must be viewed in terms of the total mission delta V requirement. Physical limits on the ballute integrity, in terms of collapsing because of delta pressure conditions, is also a concern. Finally, there is uncertainty regarding stability control authority. The reference ballute configuration previously described in section 3.1 was used for this analysis, including a constant ballute diameter for all TR's. The most demanding of the three STS atmospheres available at this time is that of STS-2 and represents what will probably be 3 sigma values.

As indicated earlier, one impact of TR is that of delta V correction after the aeromaneuver to achieve the desired apogee conditions. The left plot of figure 4.1-2 shows the resulting delta Vs for the four TRs with a range of over 1800 fps for TR=1.1 to nearly zero for 2.2. The majority of the delta V is associated with the apogee correction although a small increment results from the error in plane (inclination) which occurs during the maneuver. These values must be considered in context of the total propulsive delta V for the mission which is nearly 19,700 fps.

OTV-780

CONCEPT

TURNDOWN RATIO (TR)

$$= C_D A \frac{MAX}{MIN}$$

TR OPTIONS

1.1

1.25

1.5

2.2
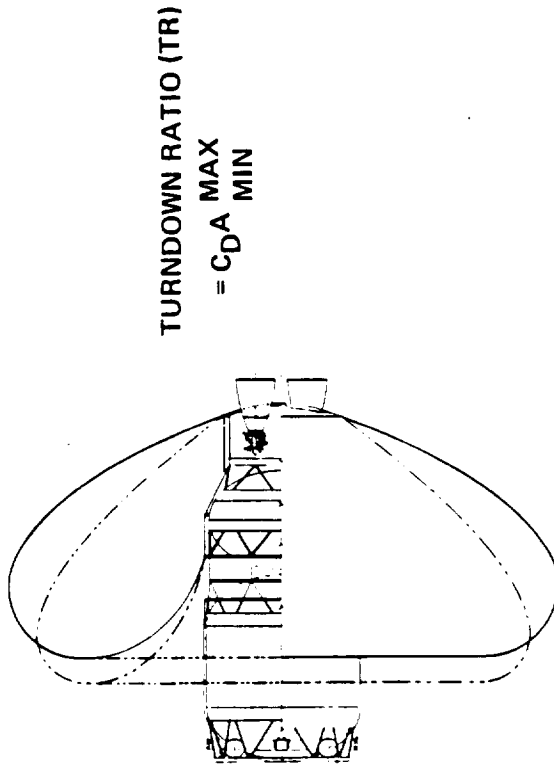
KEY GROUNDRULES

- REFERENCE BALLUTE CONFIGURATION
- MAXIMUM DIAMETER (50 FT)
- STS 2 ATM
- ENTRY WEIGHT = 20600 LBS

KEY ISSUES

- DRAG CONTROL AUTHORITY
- SENSITIVITY OF PERFORMANCE AND COST TO TR
- PHYSICAL LIMITS OF TR
- STABILITY CONTROL AUTHORITY

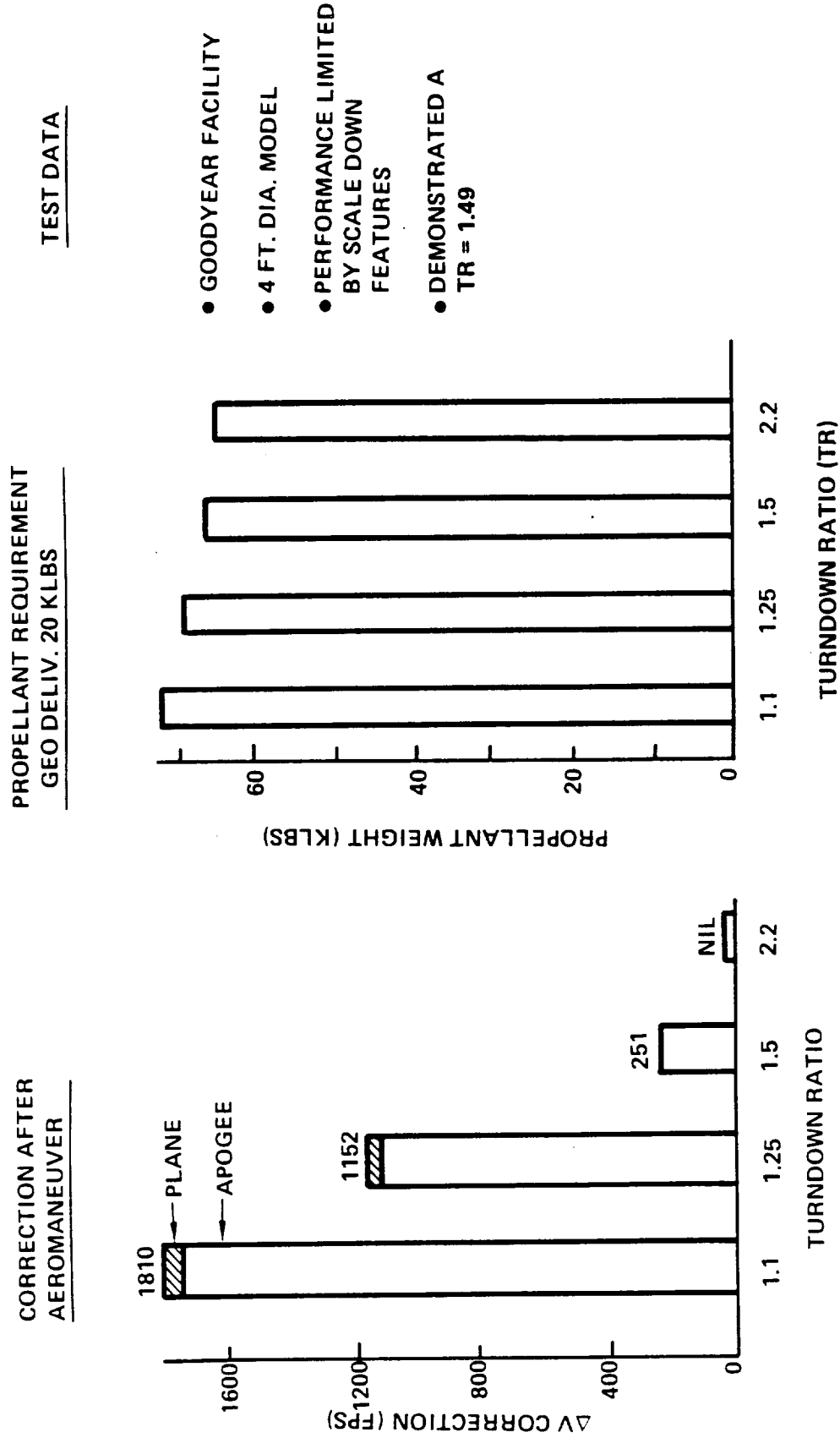*Figure 4.1-1. Ballute Turndown Ratio Trade*

Figure 4.1-2. Supporting Data Ballute Turndown Trade

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A comparison of the propellant requirement for a typical mission is also indicated in figure 4.1-2. It will be noted that the additional 1800 fps for TR of 1.1 translates into an extra 7000 lbs of propellant relative to a TR=2.2.

Also shown is a brief summary of test data that has been obtained through the Boeing/Goodyear AFE study. A TR of 1.49 was demonstrated and post analysis of the data indicated the value was limited to a large degree by the design concept employed and the ability to scale down all of the necessary features associated with the ballute.

The LCC comparison for the candidate TRs is presented in figure 4.1-3. The total OTV program undiscounted cost comparison shows a small advantage for the TR of 2.2 vs. 1.5. This difference is strictly related to the slightly better performance as a result of requiring essentially no delta V correction after the aeromaneuver versus 250 fps for a TR=1.5. When discounting is applied there is essentially no difference between the TR of 1.5 and 2.2.

The time phased LCC comparison is presented in figure 4.1-4. The cum cost difference between the reference concept using a TR=1.5 versus the other alternatives is indicated. Because there is no difference in DDT&E between the concepts the indicated difference is strictly reflecting the operations cost with the TR of 2.2 giving a small advantage over 1.5.

The ballute aerodynamic stability is important because it restricts the center of gravity location when the requirement for positive static margin is imposed. Static margin in this case is defined as the distance between the aerodynamic center (a.c.) and the center of gravity. A positive static margin requirement is necessary because the aerodynamic moments are large relative to the reaction control system (RCS) moment. The aerodynamic moment per degree alpha for a static margin of 5% of the length is as large as 1070 ft-lb as compared with an RCS moment for the current design of only 445 ft-b. The a.c..-c.g. relationships for the ballute OTV are shown in figure 4.1-5. The aerodynamic center is expressed in terms of ballute turn-down angle and is more restrictive (further upstream and closer to the center of gravity) for the lower turndown angles. For positive static margin, the aerodynamic center must be downstream of the center of gravity for the maximum turndown condition. The minimum static margin was selected as 5% of the vehicle length based on prior experience with aerodynamically stabilized vehicles. As indicated on the configuration showing both c.g. and a.c. data, the 5% margin is available for the worst case situation.

Our recommendation is to baseline a turndown of 1.5. The cost penalty for this TR is extremely small compared to a TR of 2.2 and most importantly the TR of 1.5 has already been demonstrated. In summary, the delta V for apogee correction after the
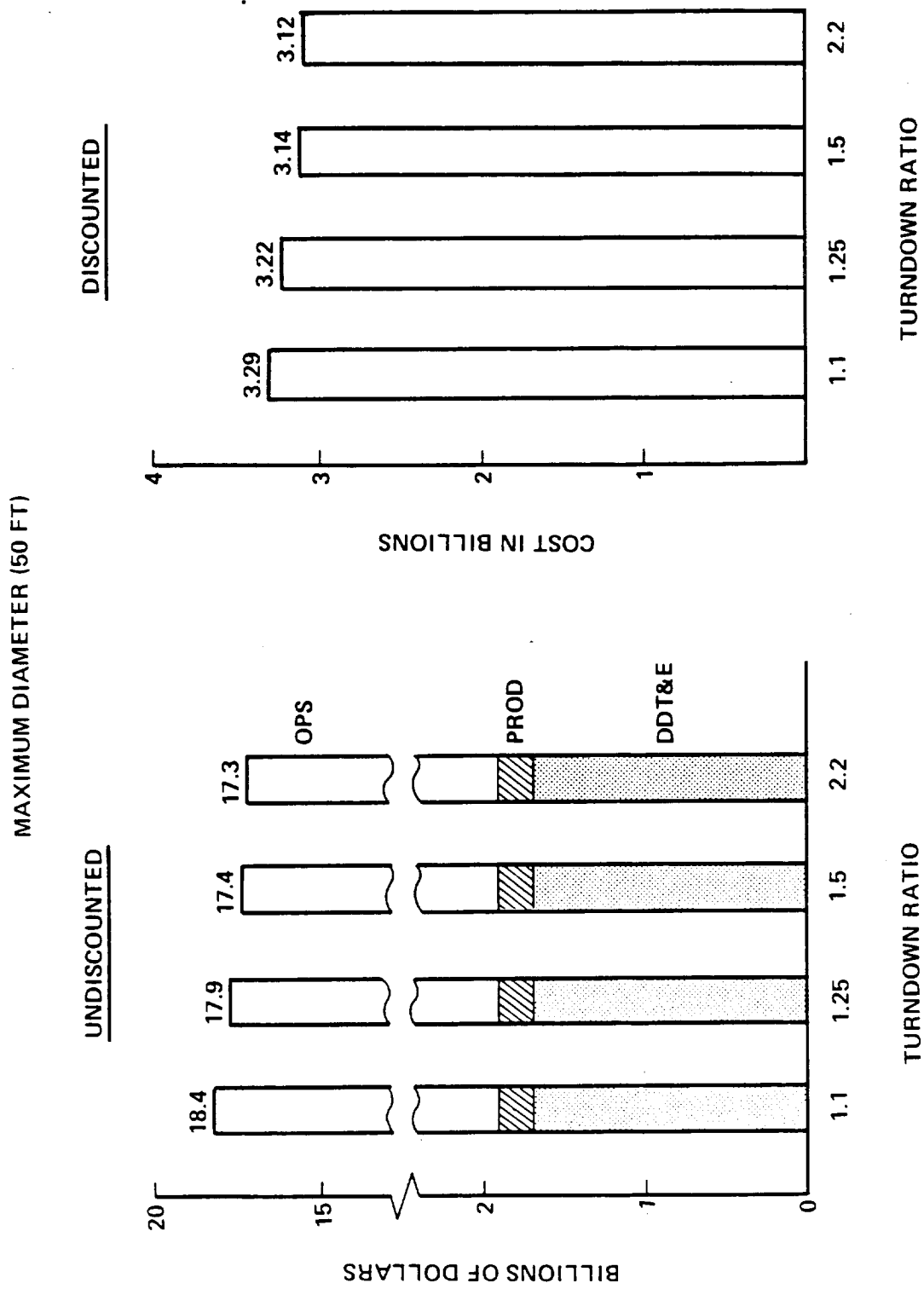
Figure 4.1-3. Ballute Turndown Influence on OTV Program LCC

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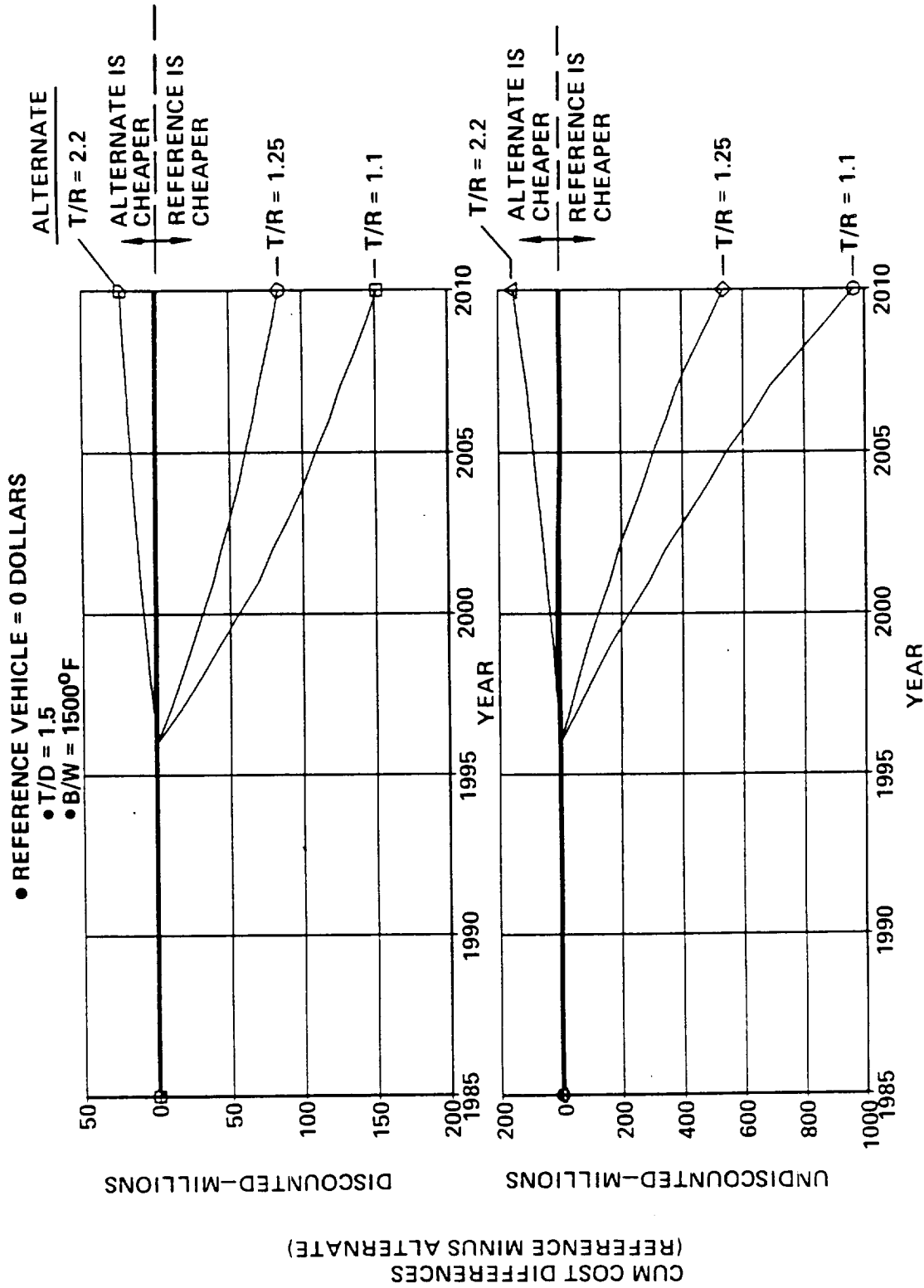
Figure 4.1-4. OTV Time Phased LCC Comparison Ballute Turndown Influence

Figure 4.1.5 A.C. — C.G. Relationship for Aerodynamic Stability

- BALLUTE IS SIZED SO THAT THE C.P.—C.G. MARGIN IN THE MAXIMUM TURNED-DOWN CONDITION IS AT LEAST 5% OF THE MEAN AERODYNAMIC LENGTH.

- THE AERODYNAMIC CENTER CAN BE EXPRESSED AS A FUNCTION OF BALLUTE CONE ANGLE OR TURNDOWN.
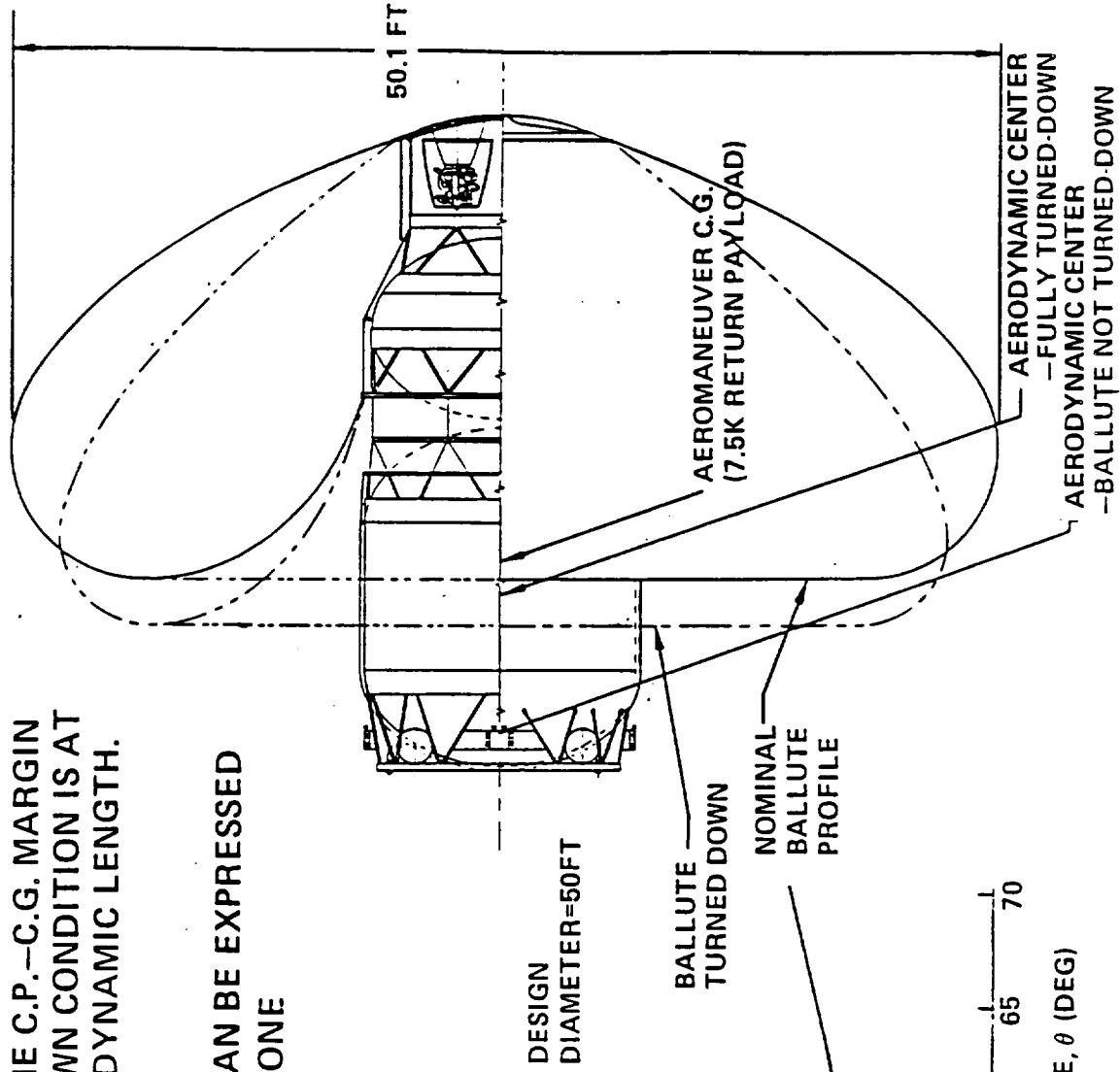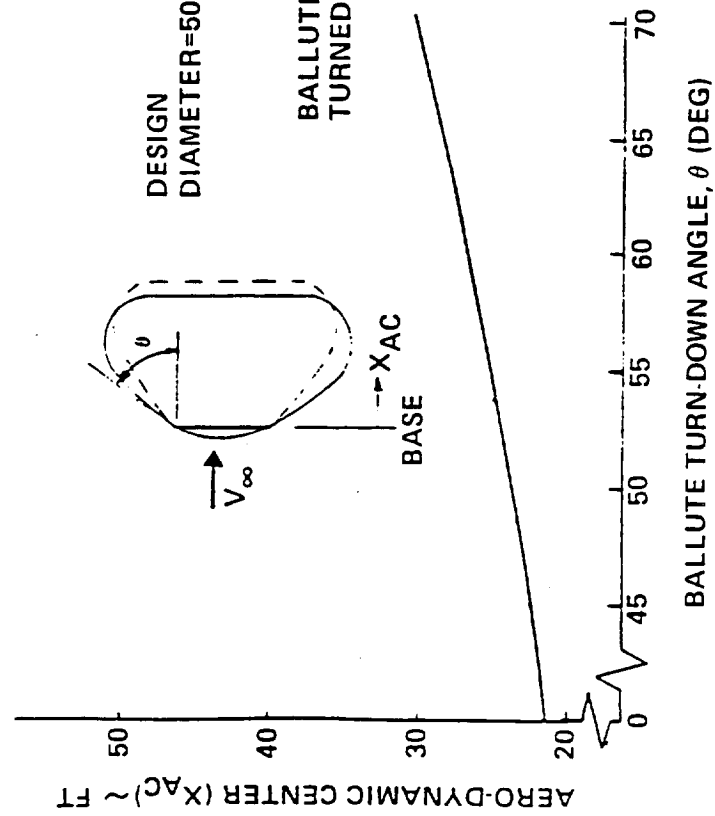
aeromaneuver is relatively small compared to the total propulsive delta V requirement and does not justify from a cost standpoint a TR beyond 1.5.

4.1.2 Backwall Temperature and Drag Control Trade

The ballute backwall (B/W) temperature and drag control trades have been combined into one joint trade so that comparison of competing technologies were more apparent. Characteristics of the options considered are shown in figure 4.1-6. The B/W temperature in question is actually that which occurs at the backside of the material on the front surface of the ballute. The backwall temperature options of 600°F and 1500°F require different materials used for the flexible surface insulation (FSI). In the case of the 1500°F concept, Nextel with CS 105 (a sealer that is currently available) is required as well as more insulation along the body of the OTV.

Besides the turndown method previously discussed for drag control another option is the use of jet flow from the main engine to modulate or vary the amount of on coming air flow and thus the drag experienced by the vehicle. Operating the main engine from a tank head to pump idle provides a 10 to 1 ratio in drag coefficient.

A more in depth discussion concerning the TPS aspects of these options can be found in Volume II, Book 3.

Data pertaining to OTV dry weight and propellant differences for combination of B/W temperature and drag control method are presented in figure 4.1-7. The reference ballute OTV concept used a TR=1.5 and 600°F B/W. Going to a 1500°F B/W reduced the OTV dry weight by 933 lbs primarily as a result of significantly less TPS on the ballute although some insulation is required along the body of the OTV. The additional structure weight is due to the use of Nextel rather than Kevlar. Maintaining the 600°F B/W but using engine modulation for drag control was also lighter than the reference OTV by 466 lbs primarily as a result of less structure associated with the engine compartment and TPS and thus less propellant however, the gain was reduced by the propellant for the delta V correction after the aeromaneuver as well as inflation gas. Going to a 1500°F B/W with engine modulation has the greatest weight savings as it incorporated the advantages of both high performance concepts.

Propellant requirements for these options relative to two typical missions is also indicated. The 1500°F B/W and engine modulation concept requires the least amount of propellant but by less than a 1000 lbs over the 1500°F B/W, TR=1.5 concept.

The LCC comparison of the options is shown in figure 4.1-8. Due to its performance characteristics, the system using 1500°F B/W and engine modulation provides the least cost. The range of undiscounted LCC cost between the options

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DRAG CONTROL OPTIONS

① $\underline{\text{TURNDOWN} = 1.5}$ △

△ $C_D A \dfrac{MAX}{MIN}$

② ENGINE MODULATION

TANK HEAD TO PUMP IDLE GIVES 10/1 RATIO IN BALLUTE DRAG COEFFICIENT

SHOCK

JET FLOW

B/W TEMPERATURE OPTIONS

① 600°F

KEVLAR/VITON

FSI

RSI

② 1500°F

NEXTEL/CS105

FSI

RSI
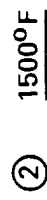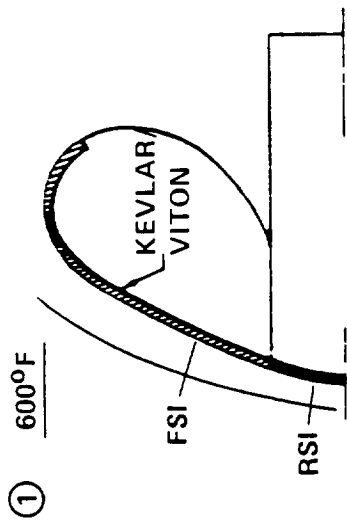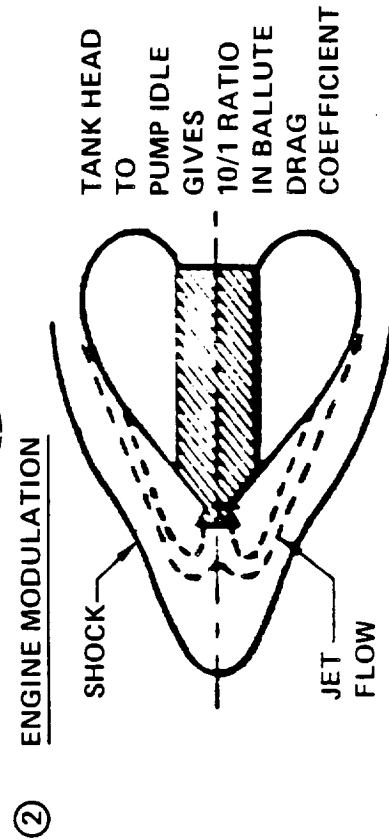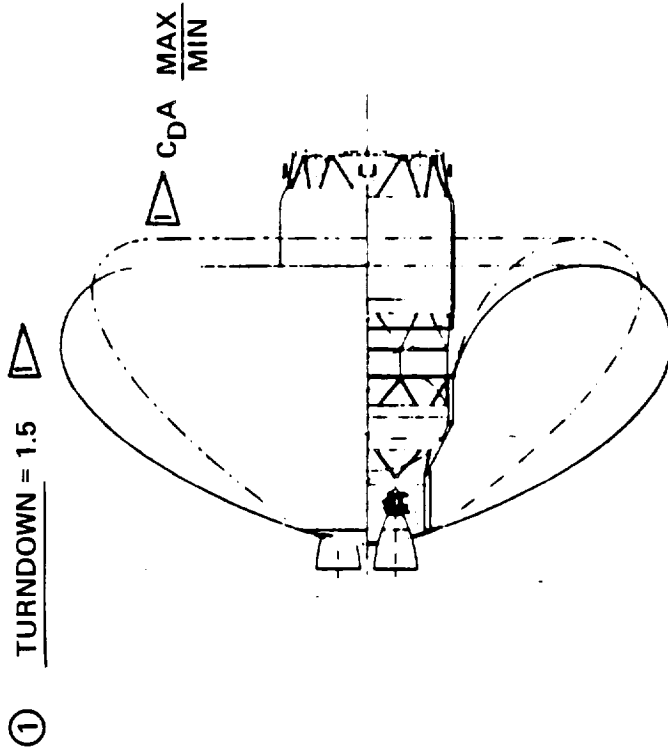
Figure 4.1-6. Ballute OTV Backwall Temperature and Drag Control Trade

OTV-737

MISSION PROPELLANT (TYP.)

MULTIMANIFEST (11/1 KLBS)

GEO DELIV (20/0 KLBS)
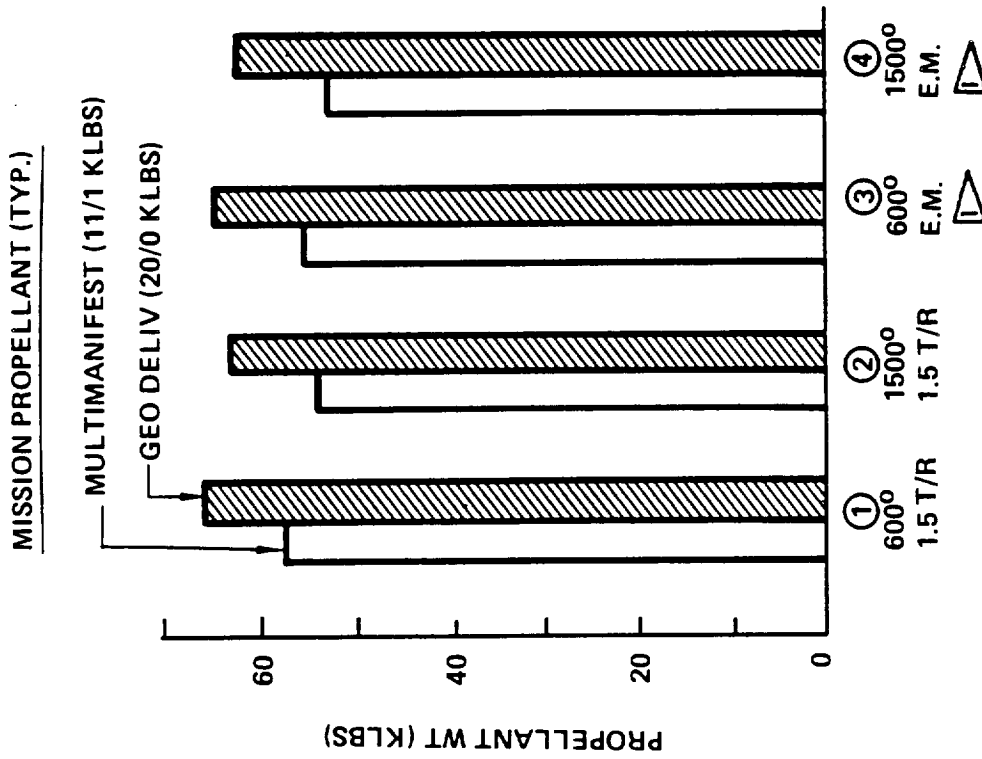
MAJOR WEIGHT DIFFERENCES

PARAMETER	① 600° 1.5 T/R	② 1500° 1.5 T/R	③ 600° E.M. △1	④ 1500° E.M. △1
● STRUCTURE	---	+ 203	– 246	– 105
● MAIN ENG. (2)	---	0	+40	+ 40
● TPS HEAT SHIELD	---	– 1	– 43	– 46
BALLUTE	---	–1460	–444	–1582
VEHICLE	---	+ 325	0	+325
● AEROMANEUVER PROPELLANT	---	0	+123	+123
● INFLATION GAS	---	0	+104	+104
TOTAL DELTA	REF.	– 933	– 466	–1141

△1 ENGINE MODULATION

Figure 4.1-7. Supporting—Data B/W Temperature and Drag Control

OTV 689
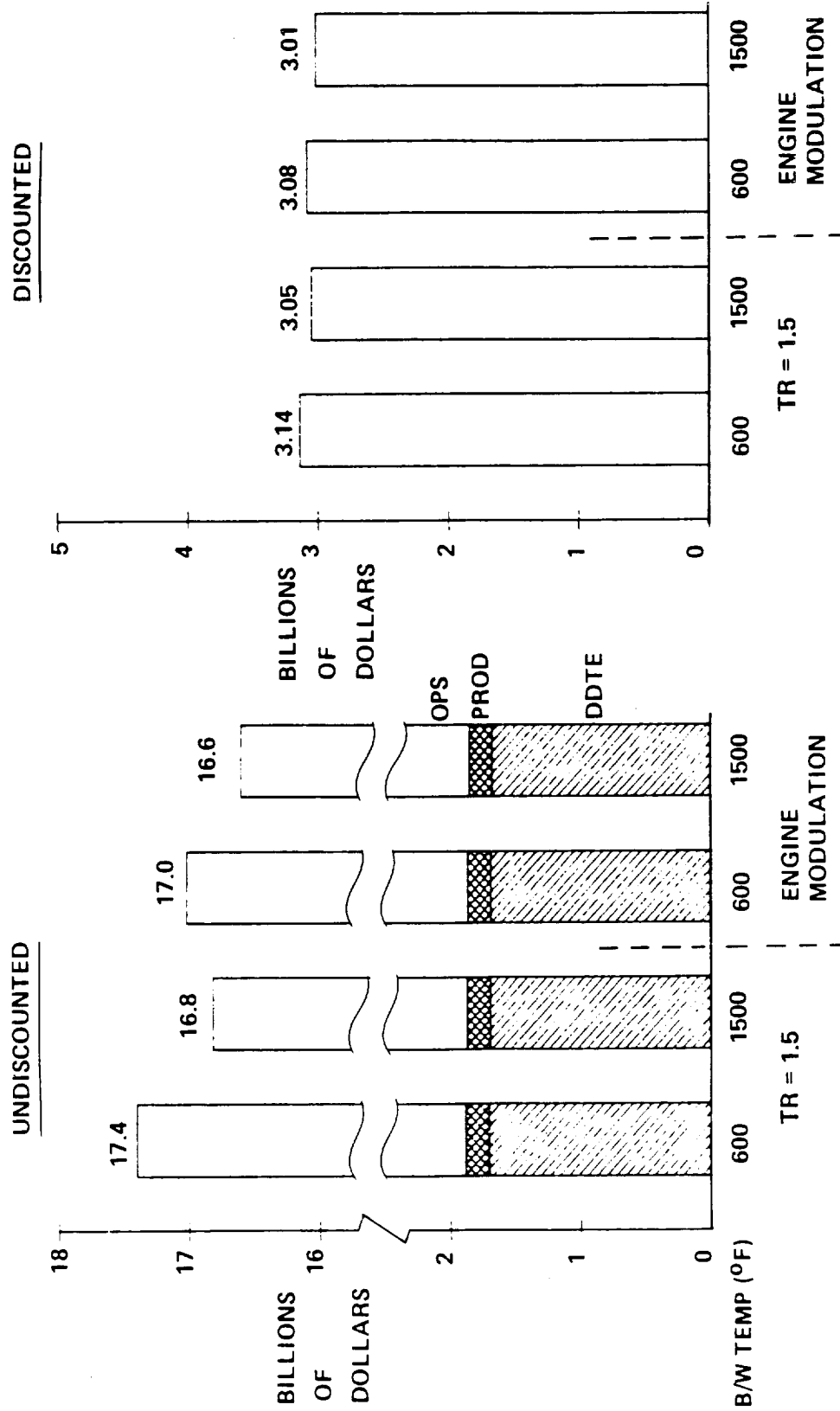
Figure 4.1-8. OTV Program LCC Comparison Ballute Backwall and Drag Control Influence

however is only about 6% with essentially no difference in DDT&E. The same trend holds true for the discounted cost comparison.

All alternates show improved time phased LCC cost characteristics relative to the reference concept as indicated in figure 4.1-9. The difference between the two 1500°F B/W concepts for the discounted case averages less than 20 million dollars with the engine modulation concept being the least cost.

Our recommendation is to baseline the ballute using a 1500°F B/W temperature and a turndown ratio of 1.5. Although this option has a small cost (1%) and performance penalty (1%) relative to the engine modulation concept there are far fewer uncertainties regarding flow interaction and engine instability. Material availability and a 5% cost advantage of the recommended system also justify it over the 600°F B/W option.

4.1.3 Baseline Vehicle

The SB ballute braked OTV resulting from our optimization studies is shown in figure 4.1-10. The stage has a diameter of 14.5 ft., a length of 35.2 ft. and a start burn weight of 74,140 lbs. when sized for a manned GEO sortie mission. The ballute used during the aeromaneuver is 50 ft. (max.) in diameter. The aerobreaking provisions include a ballute with a 1500°F backwall temperature and a turndown ratio of 1.5 (max./min. ratio of C_DA). The main engines are stowed behind the heat shield during the aeromaneuver. The ballute is used only once and the tile surface heat shield is replaced every 20 flights. No vehicle on-orbit assembly is required.

4.2 LIFTING BRAKE OTV

Trades conducted to obtain the preferred lifting brake (L/B) OTV involved configuration alternatives and variations in lift-to-drag (L/D) during the aeromaneuver.

4.2.1 Configuration Selection

The analysis conducted early in the study considered two major SB OTV configurations for lifting brake application. The concepts shown in figure 4.2-1 included an in-line two tank arrangement and a four tank concept. Due to wake heating impingement, the in-line concept required a larger diameter brake, more dry weight and propellant and resulted in a higher LCC. The four tank concept thus served as the early reference for the L/B OTV.

During the optimization studies an alternative to the four tank arrangement was developed. The comparison of the two concepts is presented in figure 4.2-2. The most significant feature of the new (third quarter) configuration is that the propellant tanks
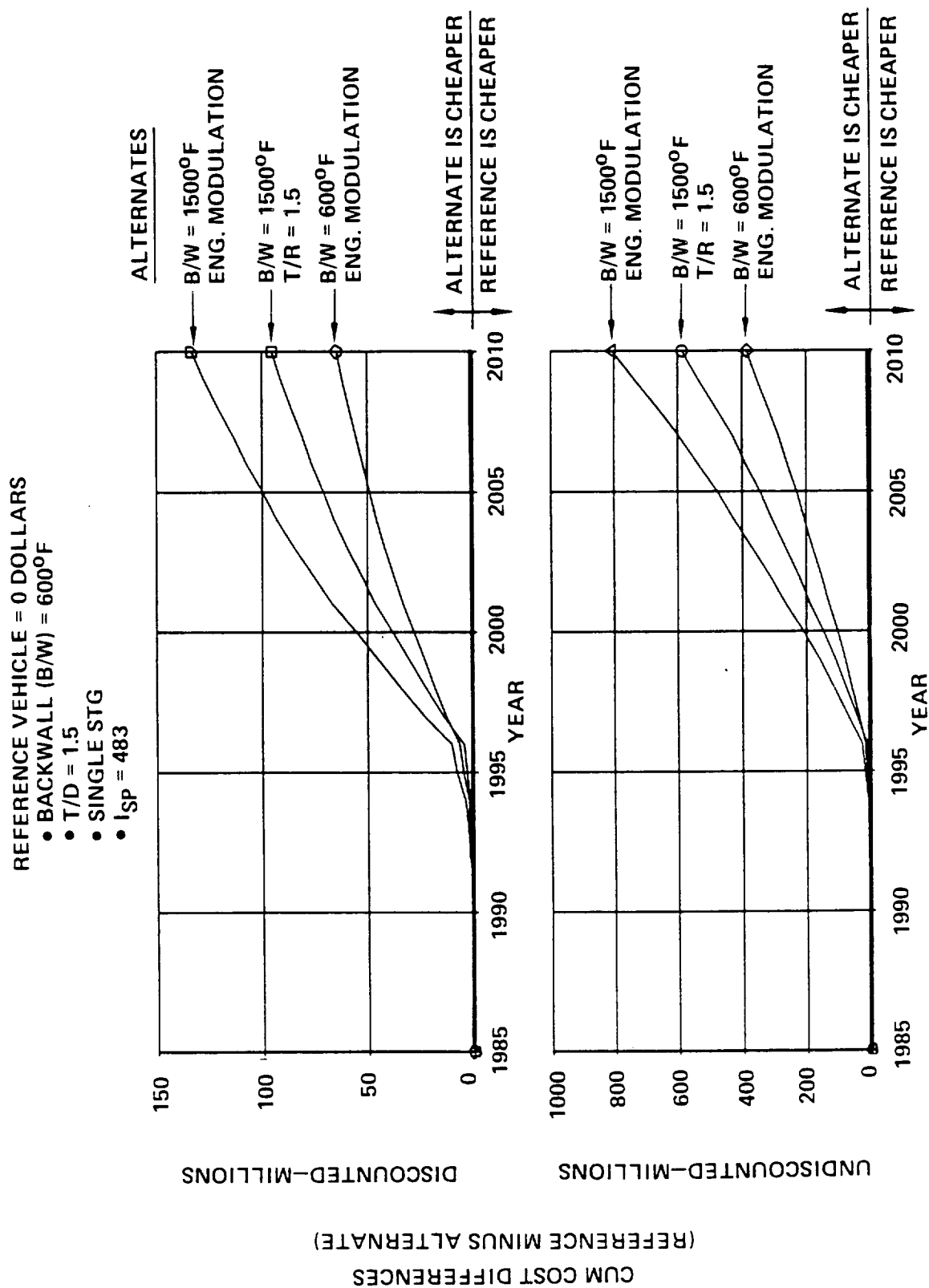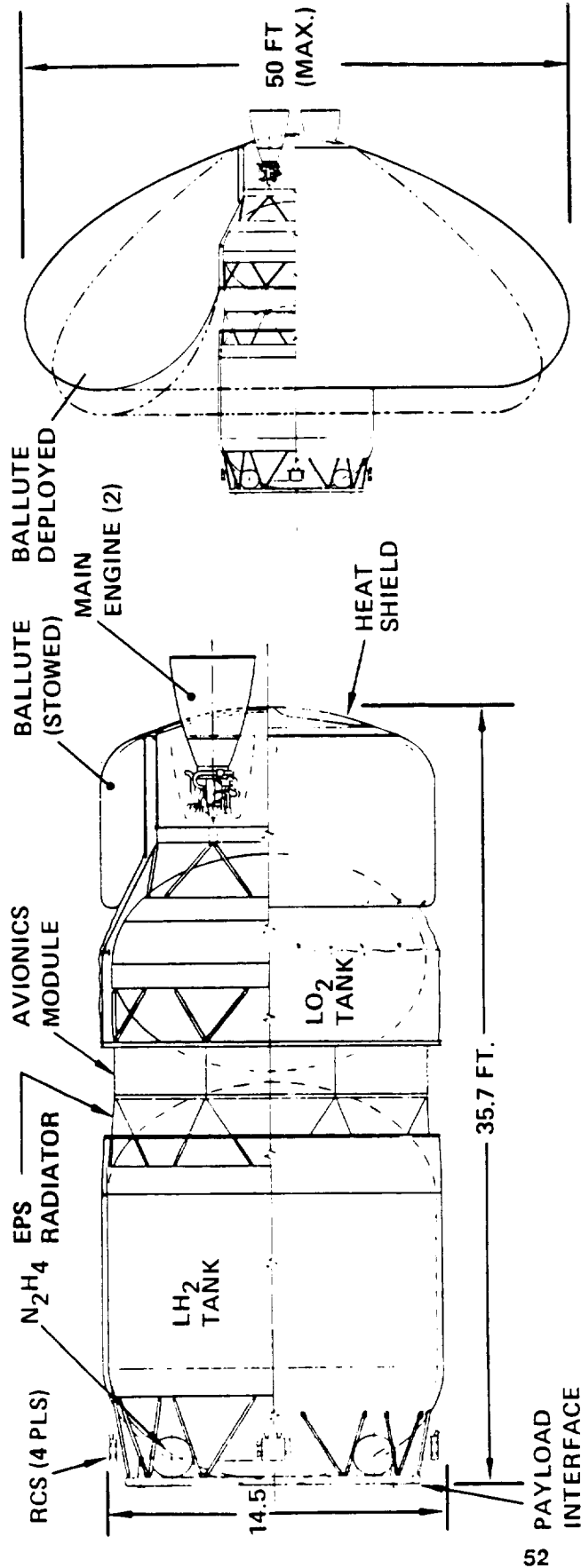
Figure 4.1-9. OTV Time Phased LCC Comparison Ballute B/W Temperature and Drag Control Trade

51

OTV-80?
Apr 86

50 FT (MAX.)

BALLUTE DEPLOYED

BALLUTE (STOWED)

MAIN ENGINE (2)

HEAT SHIELD

AVIONICS MODULE

EPS RADIATOR

N₂H₄

LH₂ TANK

LO₂ TANK

RCS (4 PLS)

14.5

35.7 FT.

PAYLOAD INTERFACE

STAGE WEIGHT SUMMARY (LBS)

- DRY   9189
- MAIN PROP.   63,890
- OTHER FLUIDS   1,061
- STARTBURN   74,140

△1 FOR MANNED GEO SORTIE (7.5K R.T.) OR 20K GEO DELIV

UNIQUE FEATURES

- BALLUTE
  - NEXTEL/CS 105
  - 1500°F BACKWALL
  - TURNDOWN RATIO = 1.5
  - 1 USE
- HEAT SHIELD—RSI
  - 20 USES
- NO INITIAL ON-ORBIT ASSEMBLY

Figure 4.1-10. SB Ballute Braked OTV

52

OTV-1780

	IN-LINE (2 TANKS)	CLUSTER (4 TANKS)
BRAKE DIA. (FT)	50	40
OTV DRY WT. (LBS)	11,200	9,300
PROPELLANT WT. (LBS) (MGSS MISSION)	72,000	63,000
LIFE CYCLE COST ($ BILLIONS)	35.0	32.8
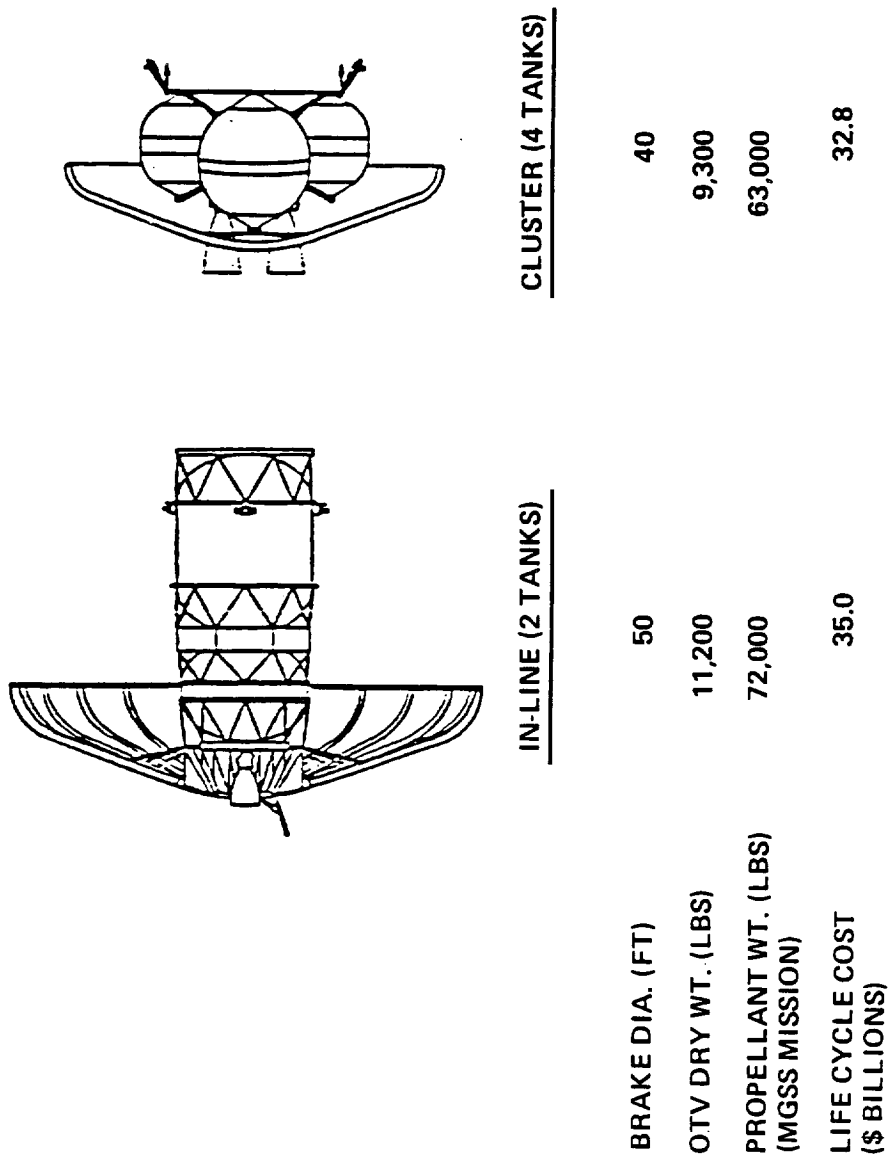
Figure 4.2-1 SB OTV Lifting Brake Options
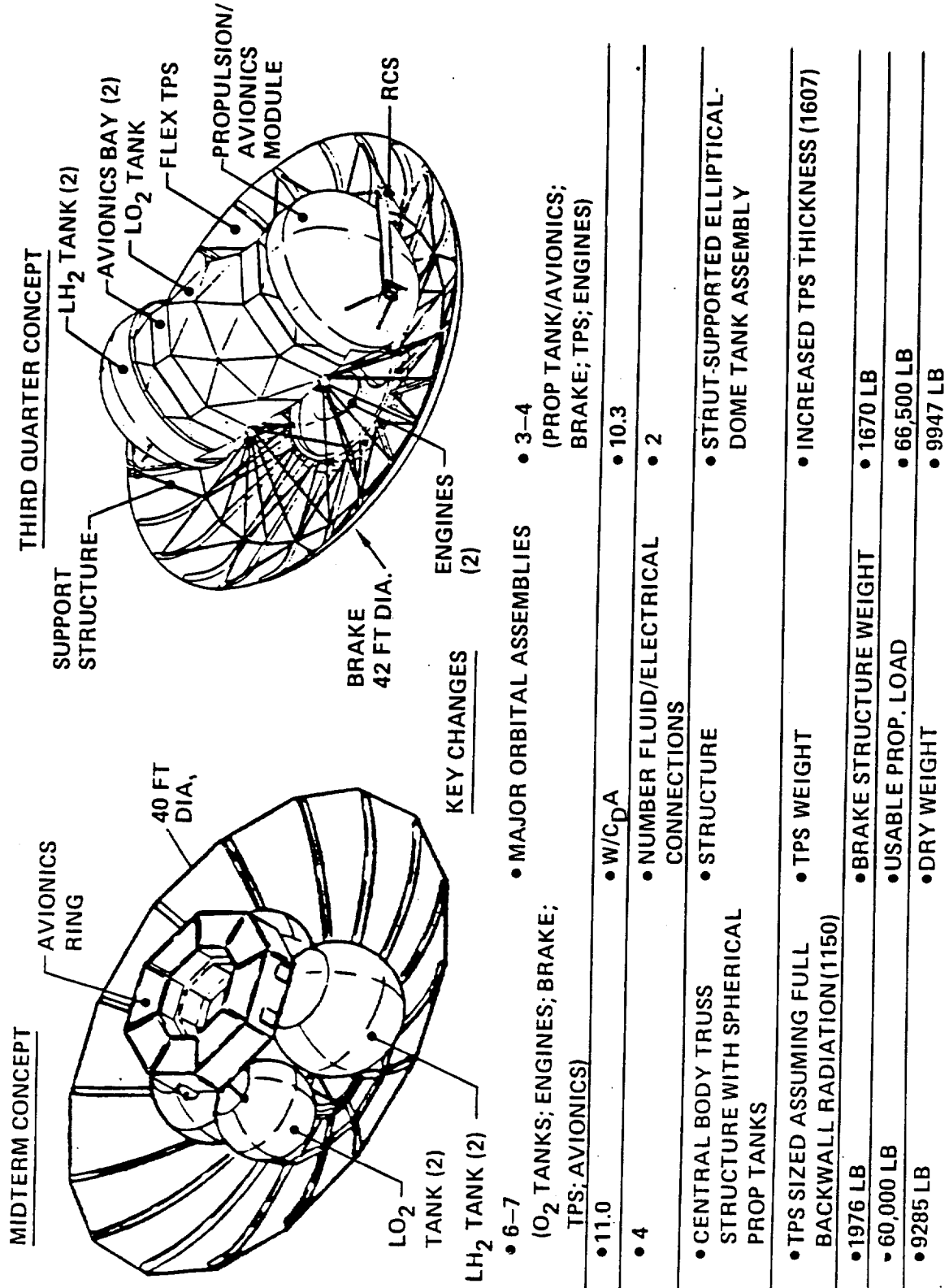
Figure 4.2.2 SB OTV Lifting Brake Configuration Trade

OTV-725

THIRD QUARTER CONCEPT

LH₂ TANK (2)
AVIONICS BAY (2)
LO₂ TANK
FLEX TPS
PROPULSION/AVIONICS MODULE
RCS
SUPPORT STRUCTURE
BRAKE 42 FT DIA.
ENGINES (2)

MIDTERM CONCEPT

AVIONICS RING
40 FT DIA.
LO₂ TANK (2)
LH₂ TANK (2)

KEY CHANGES

- MAJOR ORBITAL ASSEMBLIES
- W/C_DA
- NUMBER FLUID/ELECTRICAL CONNECTIONS
- STRUCTURE
- TPS WEIGHT
- BRAKE STRUCTURE WEIGHT
- USABLE PROP. LOAD
- DRY WEIGHT

Midterm:
- 6–7 (O₂ TANKS; ENGINES; BRAKE; TPS; AVIONICS)
- 11.0
- 4
- CENTRAL BODY TRUSS STRUCTURE WITH SPHERICAL PROP TANKS
- TPS SIZED ASSUMING FULL BACKWALL RADIATION (1150)
- 1976 LB
- 60,000 LB
- 9285 LB

Third Quarter:
- 3–4 (PROP TANK/AVIONICS; BRAKE; TPS; ENGINES)
- 10.3
- 2
- STRUT-SUPPORTED ELLIPTICAL-DOME TANK ASSEMBLY
- INCREASED TPS THICKNESS (1607)
- 1670 LB
- 66,500 LB
- 9947 LB

and avionics have been integrated into one module called the propellant avionics module (PAM). The result is less on orbit assembly both in terms of major elements and fluid and electrical connections. The major factor contributing to the weight increase over the midterm is that more in-depth thermal analysis indicated the need for an increase in TPS thickness on the brake assuming a 600°F backwall temperature. Should the midterm configuration receive the same amount of analysis as the new configuration the weight would be just as heavy. Accordingly, because of on-orbit assembly and weight considerations the new configuration employing an integrated propulsion avionics module is selected as the baseline for the symmetrical lifting brake concept.

4.2.2 Lift-to-Drag

In the lifting brake concept, lift is used to control the depth of atmosphere penetration (via banking the vehicle) during the aeromaneuver so that the desired exit condition and apogee is achieved. Lift is achieved by off-setting the c.g. so that an angle of attack is available which in turn varies the drag.

Several different lift to drag ratios (L/D) were investigated. The impact on delta V correction after the aeromaneuver to achieve the proper apogee condition and the resulting impact on performance is shown in figure 4.2-3. Data on the left shows a delta V correction ranging between 464 fps for an L/D of 0.117 to 653 fps for an L/D of 0.324 when using the STS-2 atmosphere and the other specified conditions. The correction delta V is higher for high L/D options because the higher angle of attack that is required also results in a lower C_D and drag. This in turn means the vehicle is going faster than desired as it exits the atmosphere. The impact of the delta V correction is expressed on the right side in terms of propellant requirement for two typical missions. The results indicate little difference between the L/D's and this is because the correction delta is a small fraction of the nearly 19,700 fps propulsive requirement to perform the total mission.

The LCC comparison for this trade is shown in figure 4.2-4. As would be expected with little difference in performance, the LCC comparison also shows little difference with the L/D of 0.117 providing a small advantage. The time phased comparison is shown in figure 4.2-5.

Based on the above cost data and no significant risk difference, an L/D of 0.117 is selected for the baseline.

OTV-724

MISSION PROPELLANT (TYPICAL)

GEO DELIV (43)
(20/0 K LBS)

MULTIMANIFEST (54)
(12/2 KLBS)

PROPELLANT WT (K LBS)

67.1   67.5   67.8
58.2   58.6   59

0.117   0.226   0.324

L/D

KEY INPUT DIFFERENCES

• PLAN FOR ZERO PLANE CORRECTION
• STS 2 ATM
• W/C_DA = 10.3
• CLOSED LOOP GUIDANCE

PLANE
ERROR

APOGEE
ERROR

ΔV CORRECTION (FPS) AFTER AEROMANEUVER

653
546
464

0.117   0.226   0.324

L/D
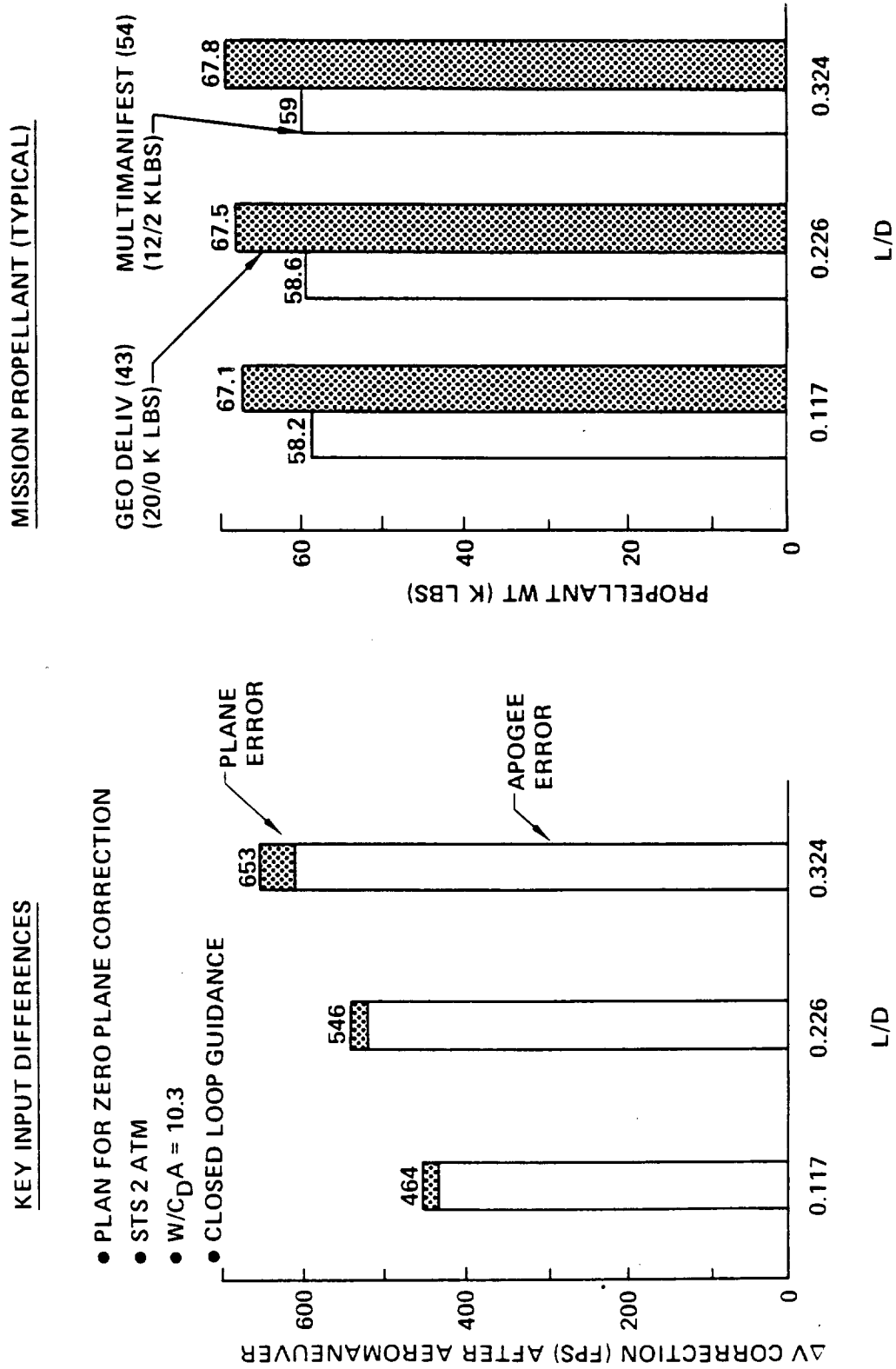
Figure 4.2.3. Supporting Data SB OTV Lifting Brake L/D Trade

56
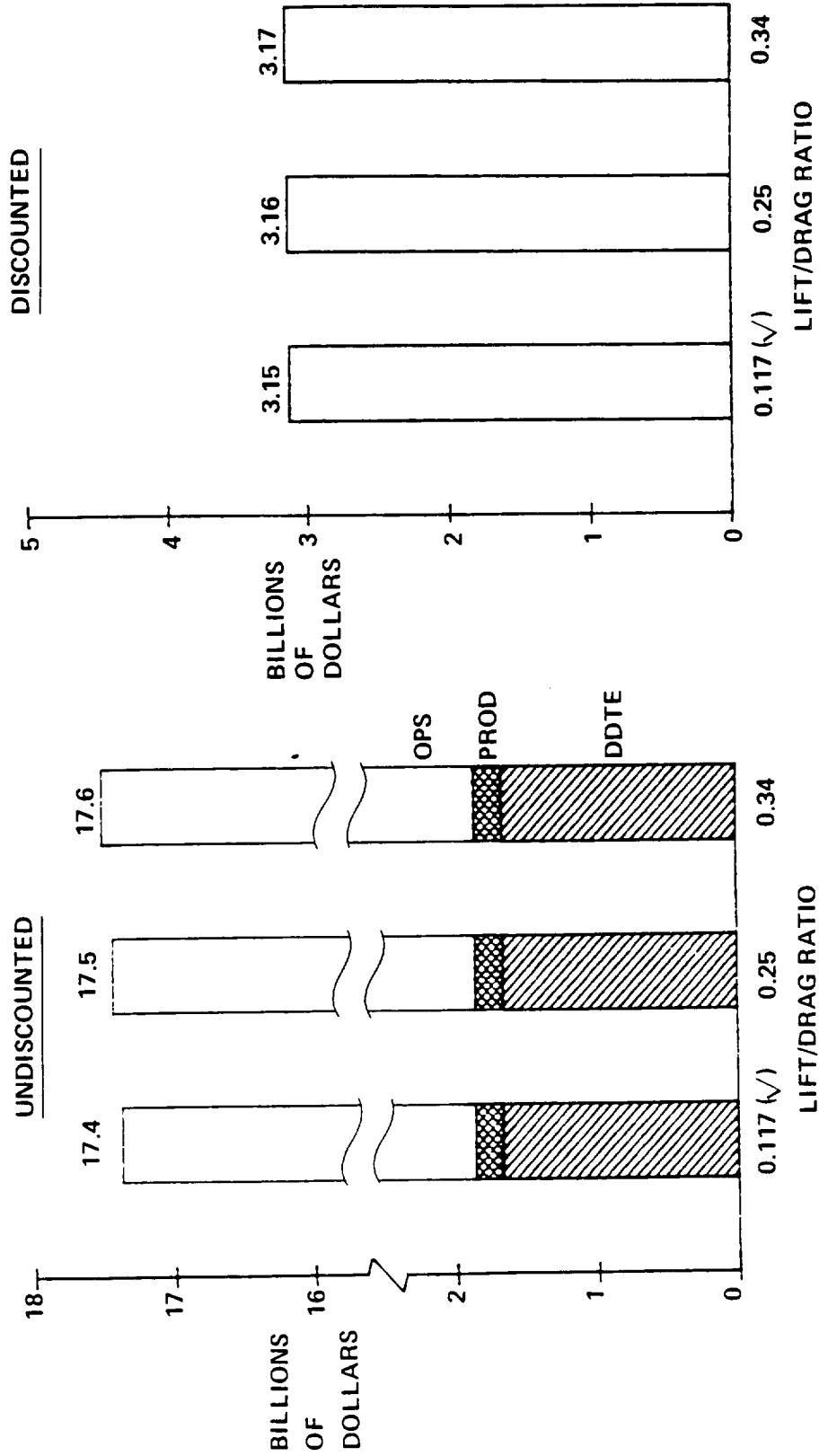
Figure 4.2.4. *OTV Program LCC Comparison Lifting Brake L/D Influence*
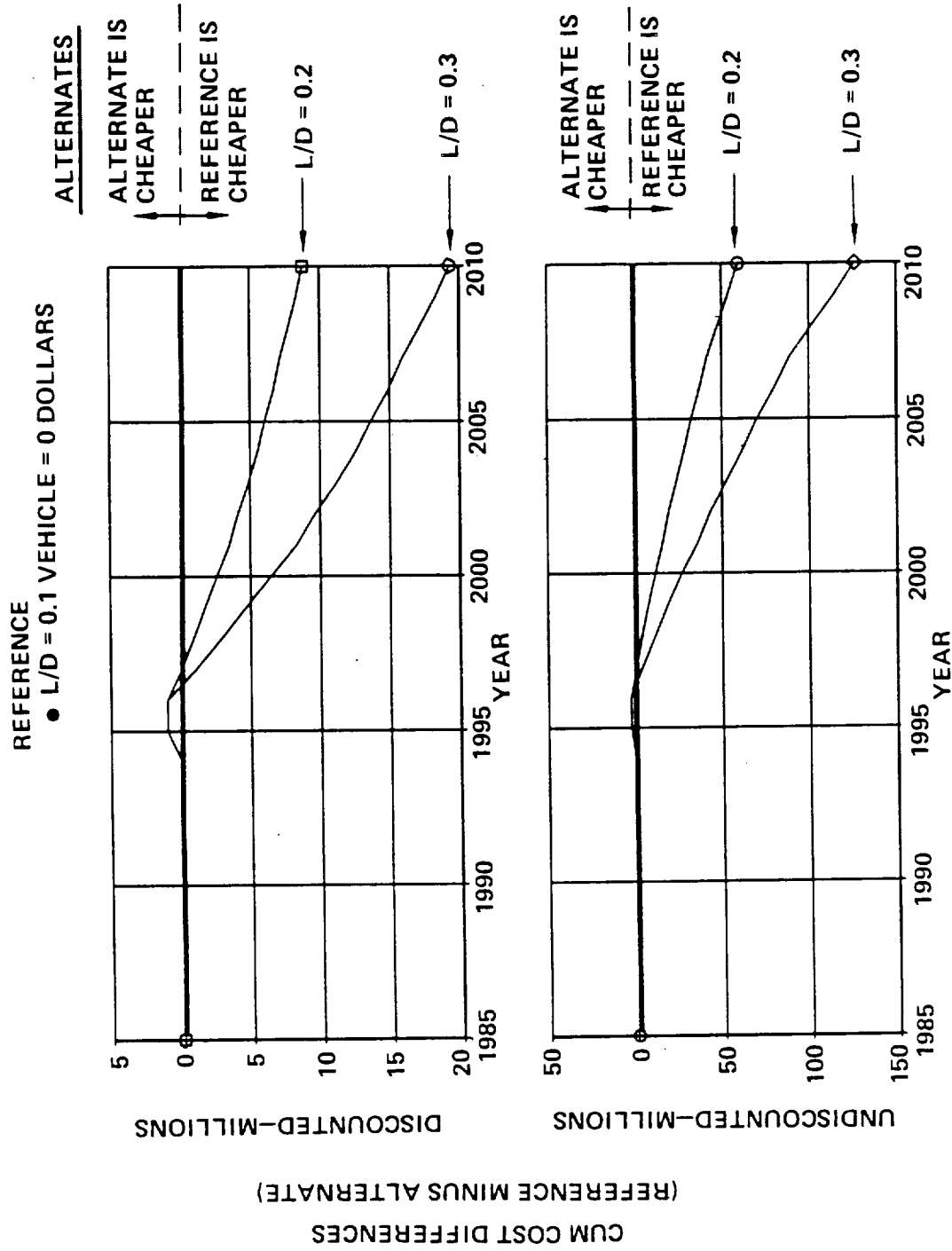
Figure 4.2-5. Time Phase LCC Comparison SB Lifting Brake L/D Trade
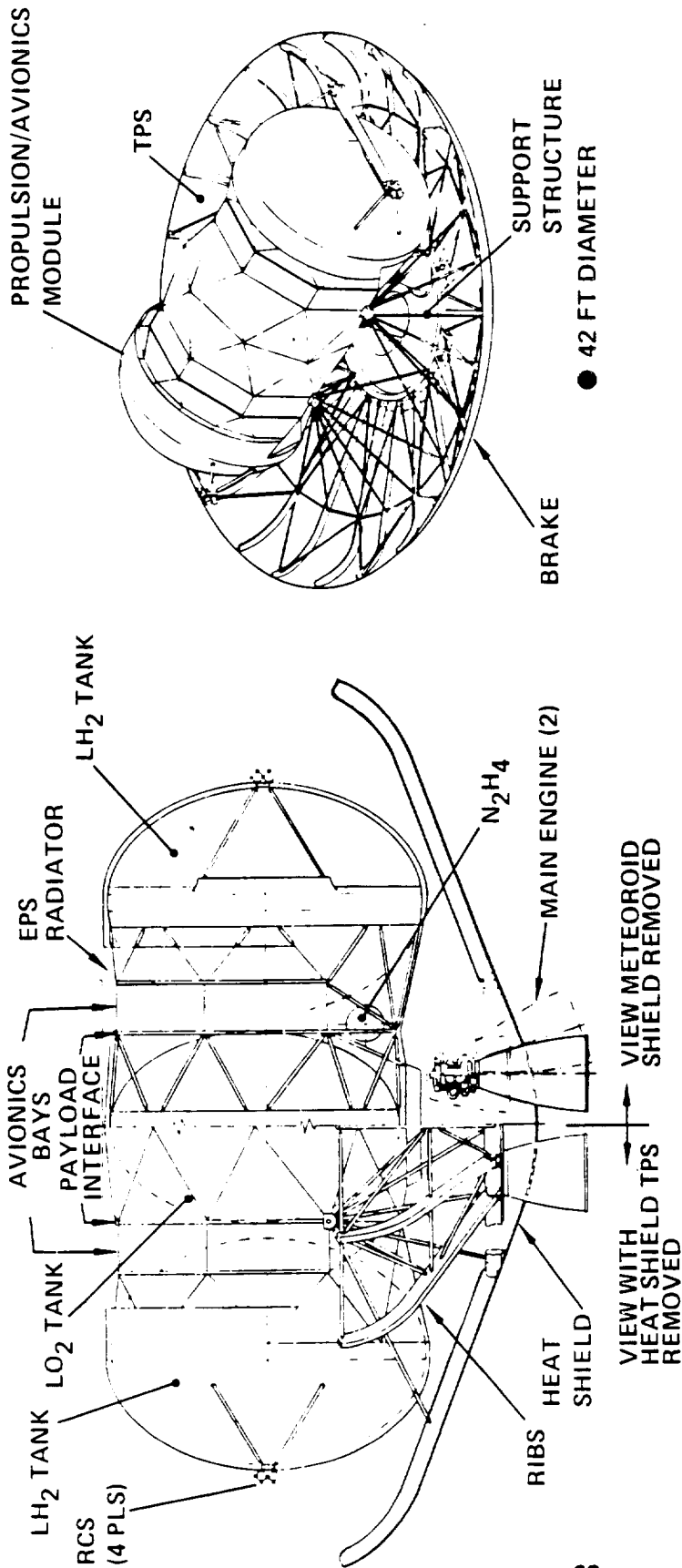
4.2.3 Baseline Vehicle

The lifting brake OTV resulting from our optimization analysis is shown in figure 4.2-6. A major feature of the configuration is that the propellant tanks and avionics have been incorporated into one ground integrated propellant/avionics module thereby reducing the amount of on-orbit assembly. The overall diameter of the brake is 42 ft. During the aeromaneuver, the vehicle flies with an L/D of 0.117 with the engines stowed behind the heat shield. The dry weight of the vehicle is 9,974 lbs and requires nearly 69,700 lbs of propellant when performing the manned GEO sortie mission.

The on-orbit assembly operations are shown in figure 4.2.-7. All elements of the lifting brake concept can be delivered in a single shuttle flight. Initially the brake structure is deployed followed by assembly of the support struts. The main engines are attached to the propellant avionics module and this unit then attached to the brake. The final step involves the attachment of the flexible TPS to the brake. The flex TPS has not been attached to the brake during launch for several reasons. One, the brake structure itself can be supported more securely so that its dynamic frequency during launch satisfies shuttle requirements. Second, we are uncertain of the dynamic response of the flex TPS if it was "rather loosely" attached to the structure during launch. And finally, the flex TPS by study groundrules is to be replaced every 5 flights. However, the brake structure is good for 40 flights. Thus there is the requirement to launch the TPS separately and have the ability to install it on-orbit.

4.3 SHAPED BRAKE OTV

4.3.1 Configuration Selection

Early configurations for this concept tended to be similar to those originally proposed by NASA JSC. The comparison of this concept with one developed by Boeing during the third quarter is presented in figure 4.3-1. Several major differences exist between the two concepts. One change in the Boeing concept is the use of an integrated propulsion and avoinics module (PAM). This PAM differs from the L/B concept in that the main engines can also be included because they are installed on the aft end rather than perpendicular to the PAM. The other major change is the use of a 3 piece rigid brake rather than 7 to 9 pieces used in the midterm configuration. Advanced shuttle tiles are used in both cases. It will also be noted that the brake is now elliptical rather than circular in plan form in order to accommodate the PAM, however, the W/C_DA remained nearly the same.

OTV-799

PROPULSION/AVIONICS MODULE

TPS

SUPPORT STRUCTURE

BRAKE

● 42 FT DIAMETER

LH₂ TANK

EPS RADIATOR

AVIONICS BAYS

PAYLOAD INTERFACE

LH₂ TANK

LO₂ TANK

RCS (4 PLS)

N₂H₄

MAIN ENGINE (2)

VIEW METEOROID SHIELD REMOVED

HEAT SHIELD

RIBS

VIEW WITH HEAT SHIELD TPS REMOVED

STAGE WEIGHT SUMMARY (LBS)

● DRY   9,974
● MAIN PROP.   69,681
● OTHER FLUIDS   1,161
● STARTBURN   80,789

/1\ FOR MANNED GEO SORTIE (7.5K RT) OR 20K GEO DELIV.

UNIQUE FEATURES

● GROUND INTEGRATED PROPULSION / AVIONICS MODULE (PAM)

● ORBITAL ASSEMBLY OF PAM/ SUPPORT STRUCT/BRAKE/TPS

● TPS — FSI, 600° B/W
        — REPLACED EVERY 5 FLIGHTS

Figure 4.2-6. SB Lifting Brake OTV
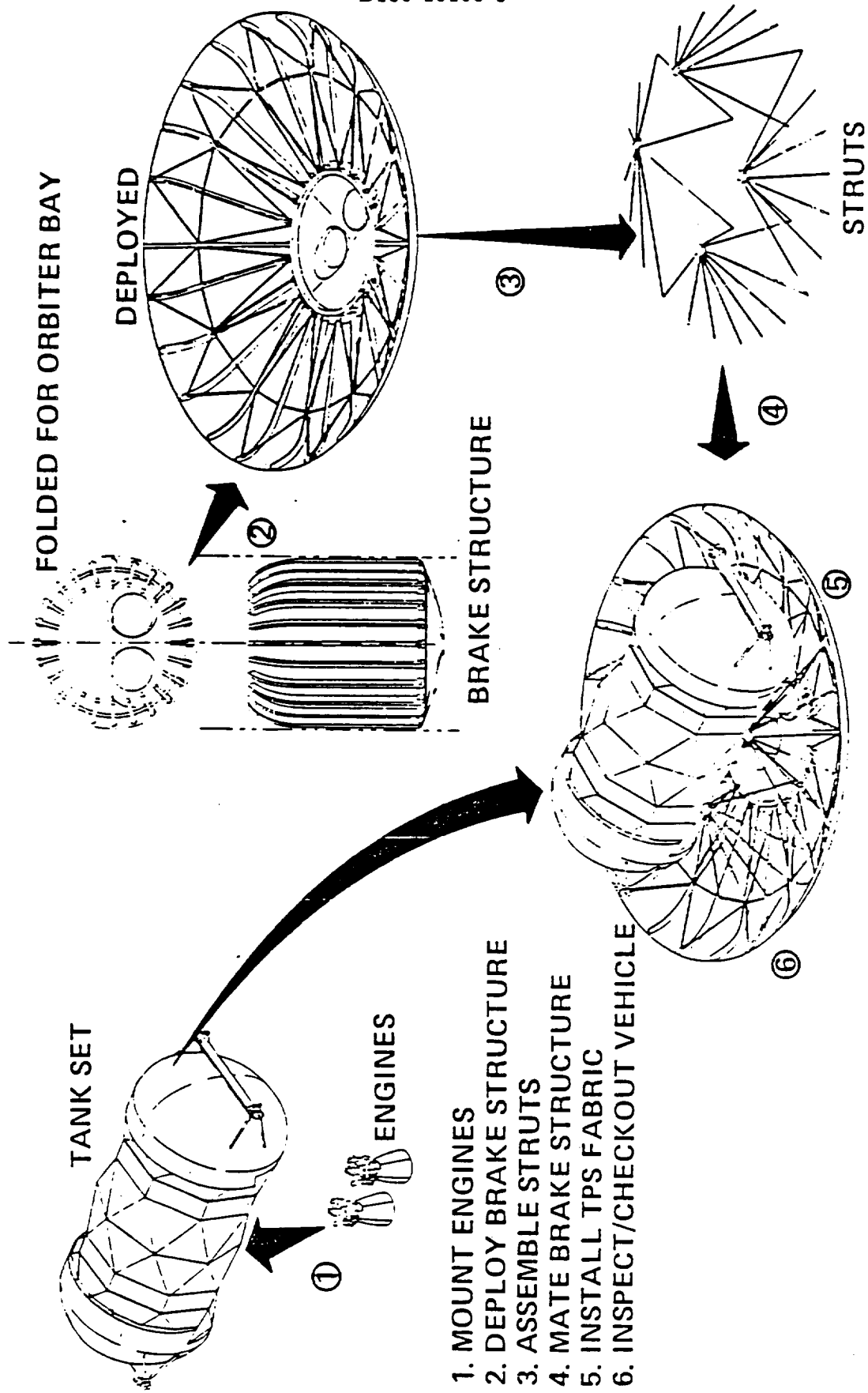
Figure 4.2-7 Lifting Brake Assembly Sequence

FOLDED FOR ORBITER BAY

DEPLOYED

STRUTS

BRAKE STRUCTURE

TANK SET

ENGINES

1. MOUNT ENGINES
2. DEPLOY BRAKE STRUCTURE
3. ASSEMBLE STRUTS
4. MATE BRAKE STRUCTURE
5. INSTALL TPS FABRIC
6. INSPECT/CHECKOUT VEHICLE

OTV-786

OTV-753

MIDTERM

THIRD QUARTER

AVIONICS BAY (2)

RIBS

RCS

LH₂ TANK(2)

KEEL

RIGID BRAKE BEAMS (3)

LH₂ TANK

LOX TANK

LH₂

LH₂ TANK

KEY CHANGES
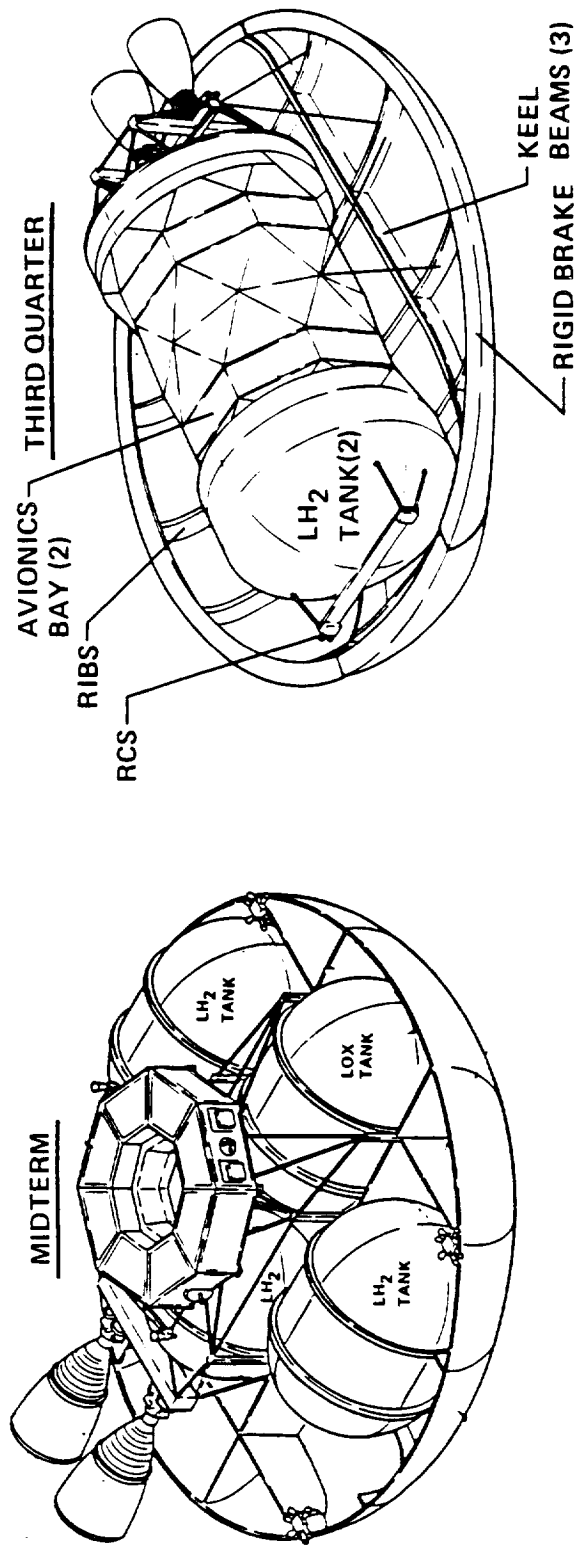
	MIDTERM	THIRD QUARTER
• SHAPE	• CIRCULAR (40' DIA.)	• ELLIPTICAL (44' X 36')
• W/C_DA	• 11.7	• 12.0
• MAJOR ORBITAL ASSEMBLIES	• 13–15 (4 TANKS, 7–9 SHELL, AVIONICS, ENGINES)	• 4 (PROPUL/AVIONICS AND 3 SHELL UNITS)
• FLUID/ELECTRICAL CONNECTIONS	• 11	• 0
• STRUCTURE	• AEROSHELL PROVIDES BACKBONE OF SYSTEM	• PROPUL/AVIONICS MODULE • PROVIDES BACKBONE
• DRY WEIGHT (LBS)	• 12,400	• 10,315
• USABLE PROP. LOAD (LBS)	• 68,700	• 67,200

Figure 4.3-1. SB OTV Shaped Brake Configuration Comparison

Several benefits resulted from the third quarter concept. One, there is far less on orbit assembly of major elements and fewer fluid/electrical connections. The PAM also has allowed a more efficient structural concept as it serves as the backbone of the configuration. The result was a significant decrease in the depth of the beams and ribs which contributed significantly to reducing the midterm dry weight of the OTV by over 2000 lbs.

4.3.2 Baseline Vehicle

Further detail on the SB shaped brake OTV resulting from our optimization analysis is shown in Figure 4.3-2. This concept has a propulsion/avoinics module (PAM) that is fully integrated on the ground. The PAM consists of two LH_2 tanks, one LO_2 tank, two avionics bays and RCS provisions. The difference between this concept and the L/B is that the engines are also included in the PAM. The rigid shell of the brake is elliptical in planform and consists of three major sections. The TPS material is advanced FRCI. Stage startburn weight for the manned GEO sortie is 82,496 lbs.

The assembly sequence for the SB shaped brake OTV is shown in figure 4.3-3. Three STS launches are required to deliver the elements to the Space Station. One launch contains the PAM, another the two outside sections of the brake, and the third the brake center section. The assembly operation consists of attaching the three brake sections, installation of the support struts, and finally attachment of the PAM indicated as the core module.

4.4 SB OTV SELECTION TRADES

Following the optimization of each of the three SB OTV aeroassist concepts they were compared to determine which would be the recommended concept in terms aeroassist and staging.

4.4.1 Aeroassist Concept Comparison

Characteristics of each of the optimized concepts are presented in figure 4.4-1. Major differences include the number of uses associated with the brake elements, the brake dry weight, OTV dry weight and propellent when sized for the manned mission. Also to be noted is that the L/B and S/B concepts require on orbit assembly while the ballute brake concept does not and that the overall size of the L/B and S/B are larger than the ballute concept at all times other than during the aeromaneuver.

In figure 4.4-2 the three aeroassist concepts are compared in terms of propellant requirement for two typical missions and the hangar size required at the Space Station.
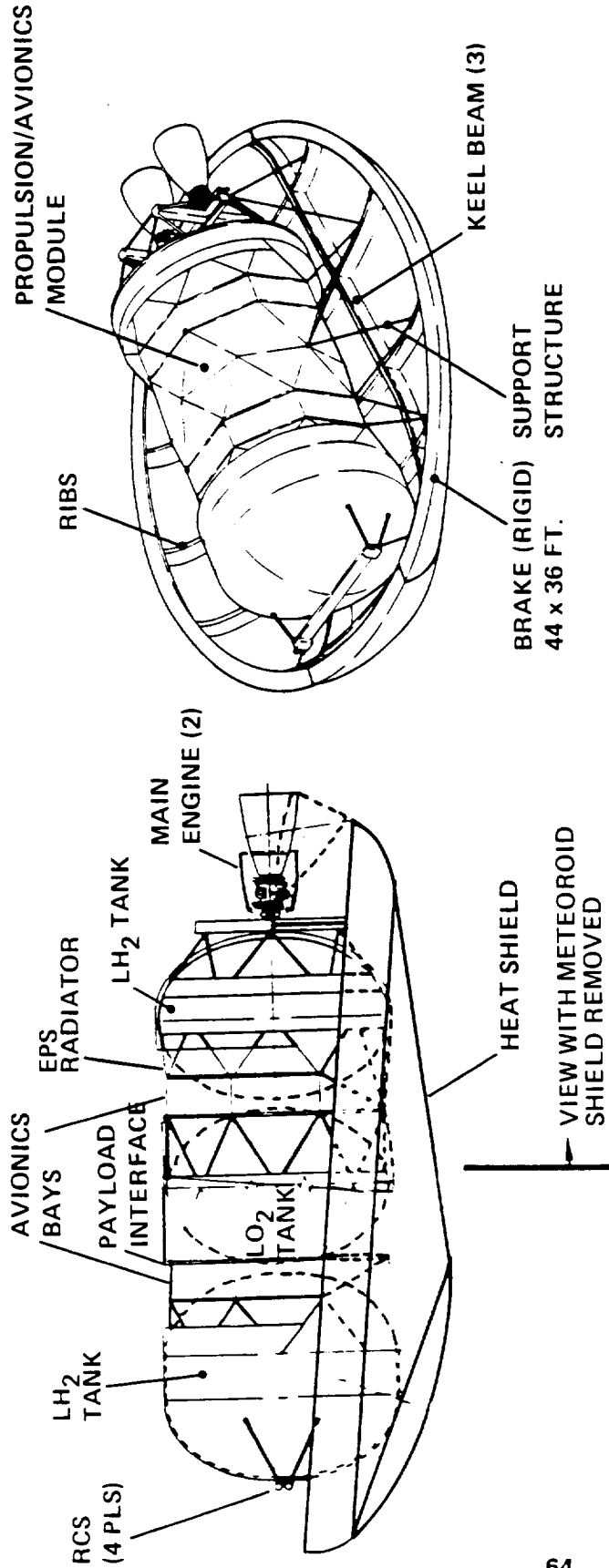
OTV-798

PROPULSION/AVIONICS MODULE

KEEL BEAM (3)

RIBS

BRAKE (RIGID) SUPPORT
44 x 36 FT. STRUCTURE

MAIN ENGINE (2)

LH₂ TANK

EPS RADIATOR

AVIONICS BAYS

PAYLOAD INTERFACE

LO₂ TANK

LH₂ TANK

RCS (4 PLS)

HEAT SHIELD

VIEW WITH METEOROID SHIELD REMOVED

STAGE WEIGHT SUMMARY (LBS)

- DRY   10,315
- MAIN PROP.   71,020
- OTHER FLUIDS   1,161
- STAGE STARTBURN   82,496

△1 FOR MANNED GEO SORTIE (7.5K R.T.)
   OR 20K GEO DELIV.

UNIQUE FEATURES

- GROUND INTEGRATED PROPULSION/ AVIONICS MODULE (PAM)

- ORBITAL ASSEMBLY OF PAM/3 BRAKE SECTIONS/SUPP. STRUCTURE

- TPS — RSI
      — REPLACE EVERY 20 FLIGHTS

- L/D = 0.23

Figure 4.3-2. SB Shaped Brake OTV

OTV-785

BRAKE SUBASSEMBLIES

CENTER SECTION

SIDE SECTION

SIDE SECTION

STRUTS

(ONE SIDE SHOWN)

CORE MODULE

1. ASSEMBLE STRUTS
2. MATE CENTER SECTION
3. MATE SIDE SECTIONS
4. INSPECT/CHECKOUT VEHICLE
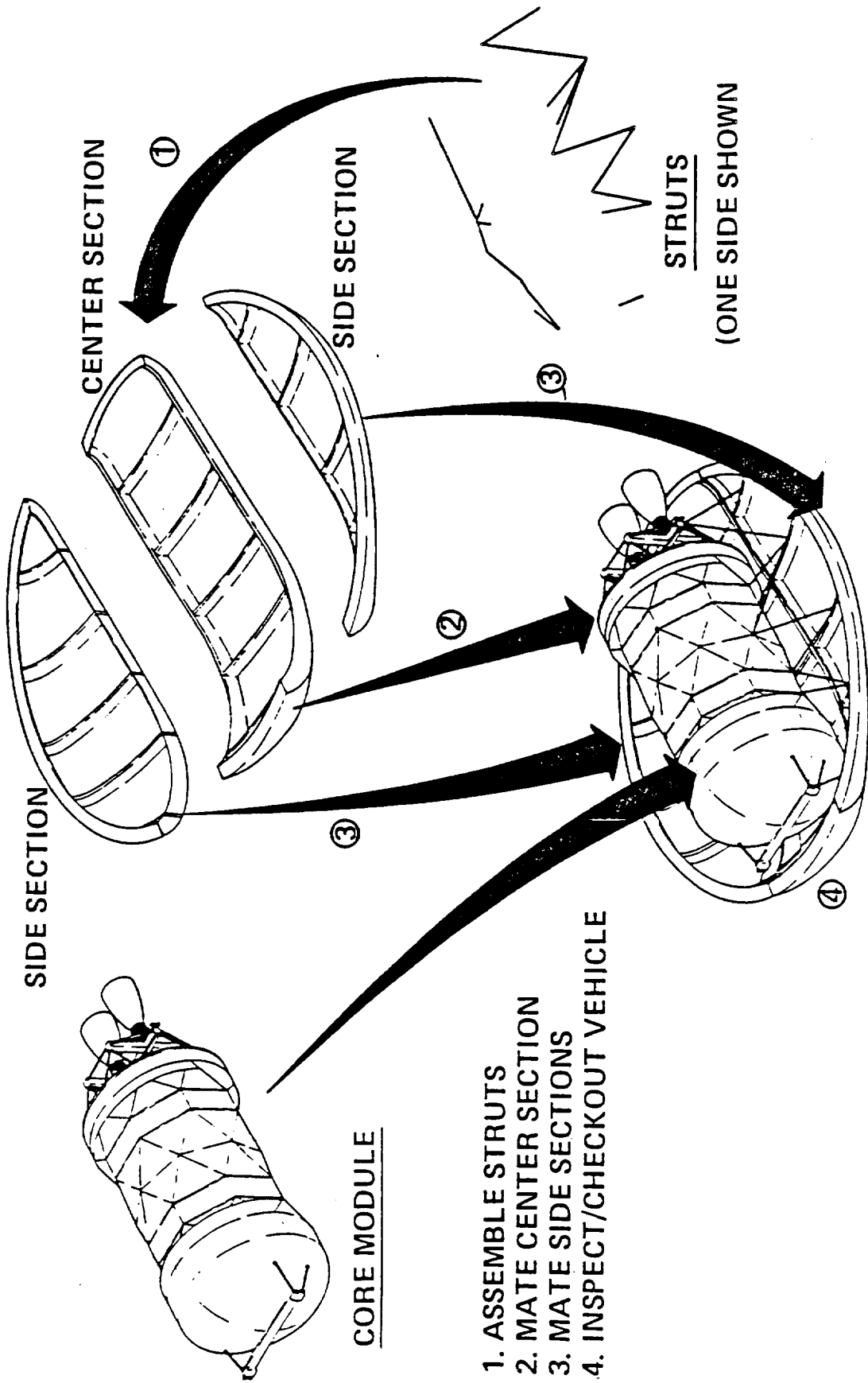
Figure 4.3.3 Shaped Brake Assembly Sequence

OTV-803
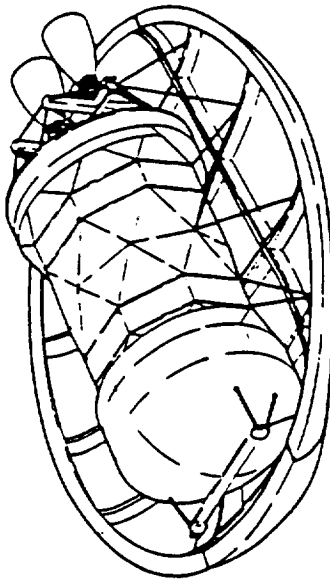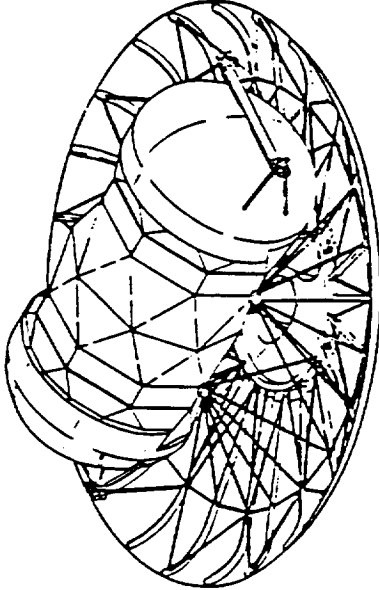
• ALL SIZED FOR GEO MAN SORTIE (7.5 K LBS R.T.)

	BALLUTE BRAKE	SYMMETRICAL LIFTING BRAKE	SHAPED BRAKE
• AEROMANEUVER FEATURES	T/D = 1.5 B/W = 1500°F	L/D = .117	L/D = .234
• INITIAL ON-ORBIT ASSY.	NO	YES	YES
• VEHICLE SIZE (FT)	14.5 x 35.7 BALLUTE 50 FT. DIA.	42 DIA.	44 x 36
• BRAKE REPLACEMENT FREQ. (FLTS)	BALLUTE (1) HEAT SHIELD (20)	TPS FABRIC (5) HEAT SHIELD (20)	HEAT SHIELD (20)
• DRY WEIGHT (LBS) (BRAKE WT.)	9189 (2712)	9947 (3276)	10314 (3608)
• PROP. WT. (LBS)	63,890	69,681	71,020

Figure 4.4-1 SB OTV Aeroassist Trade

66

Figure 4.4.2. Supporting Data SB OTV Aeroassist Trade

The dry weight difference is the principal contributor to the propellant difference with the ballute concept showing a 5% advantage over the L/B and 7% over the S/B. The hangar size for the ballute is considerably smaller than that required for the L/B and S/B because its braking device (ballute) is not deployed until the aeromaneuver.
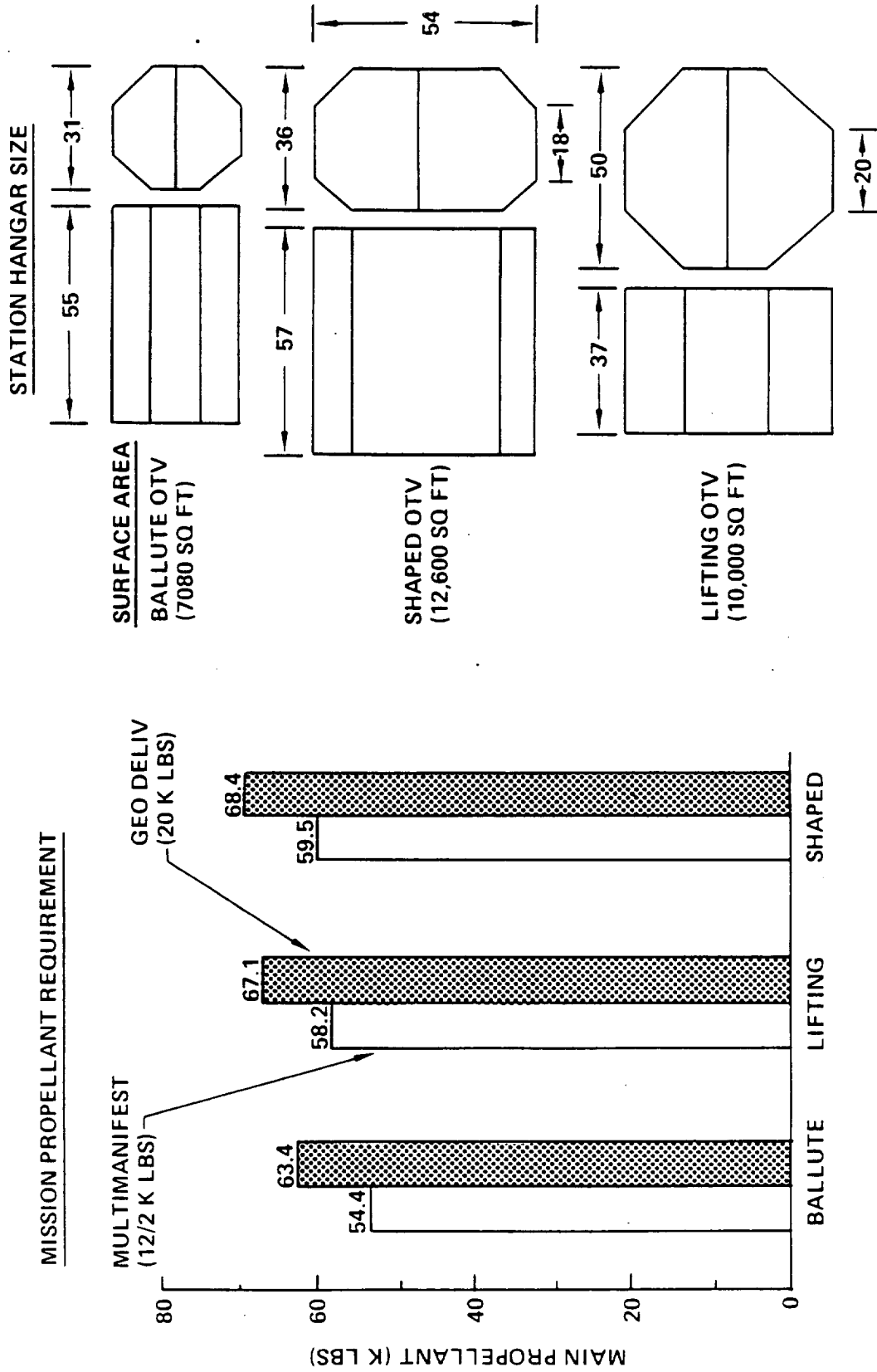
The cost comparison of these concepts is shown in figure 4.4-3. Items included in the cost are the OTV, Station accommodations, propellant tankers, and all STS launch cost associated with delivery of these elements to orbit as well as launch of the payloads to be delivered by the OTV. On an undiscounted basis, the ballute braked vehicle provides a cost advantage of 3.4% and 7.7% over the lifting and shaped brake concepts, respectively. This same trend holds true for the discounted case. The advantage of the ballute OTV is the result of having better performance characteristics and thus lower operations cost. Because there is no significant difference in DDT&E cost, the time phased LCC comparison shown in figure 4.4-4 reflects only the difference in operations cost.

Our recommendation for the SB OTV in terms of aeroassist concept is a ballute designed for a turndown of 1.5 and a backwall temperature of 1500°F. The rationale for the recommendation is shown in Table 4.4-1. This concept provides a LCC cost advantage beginning at IOC, does not require any on orbit assembly, requires a smaller hangar at the Station, and due to its performance characteristics is more forgiving in terms of increases in payload requirements. Finally, the ballute concept is judged to be the most adaptable to incorporation into either a space based or ground based OTV without any additional STS hardware such as aft cargo compartments.

A final note on this comparison involves work performed on the symmetrical L/B OTV after the aeroassist trade was completed. This work occurred in conjunction with refinements in the ACC OTV concept during the fifth quarter. Specifically if dealt with an update of the brake rib structure and thermal protection system. The weight improvement in these areas lead to performance gains so that the propellant load was reduced by 4500 lbm (see Vol. II, Book 2, Sec. 2.2.2). This improvement still resulted in the symmetrical L/B concept requiring 1300 lbm more propellant than the ballute OTV. Accordingly the LCC would be closer, however the recommendation for the ballute would remain.

4.4.2 Staging

Trades up to this point in the SB OTV analysis have relied on use of a single stage vehicle sized by the worst case mission in the low model. Using the selected SB OTV aeroassist concept (ballute braked) an alternative concept was investigated in the form
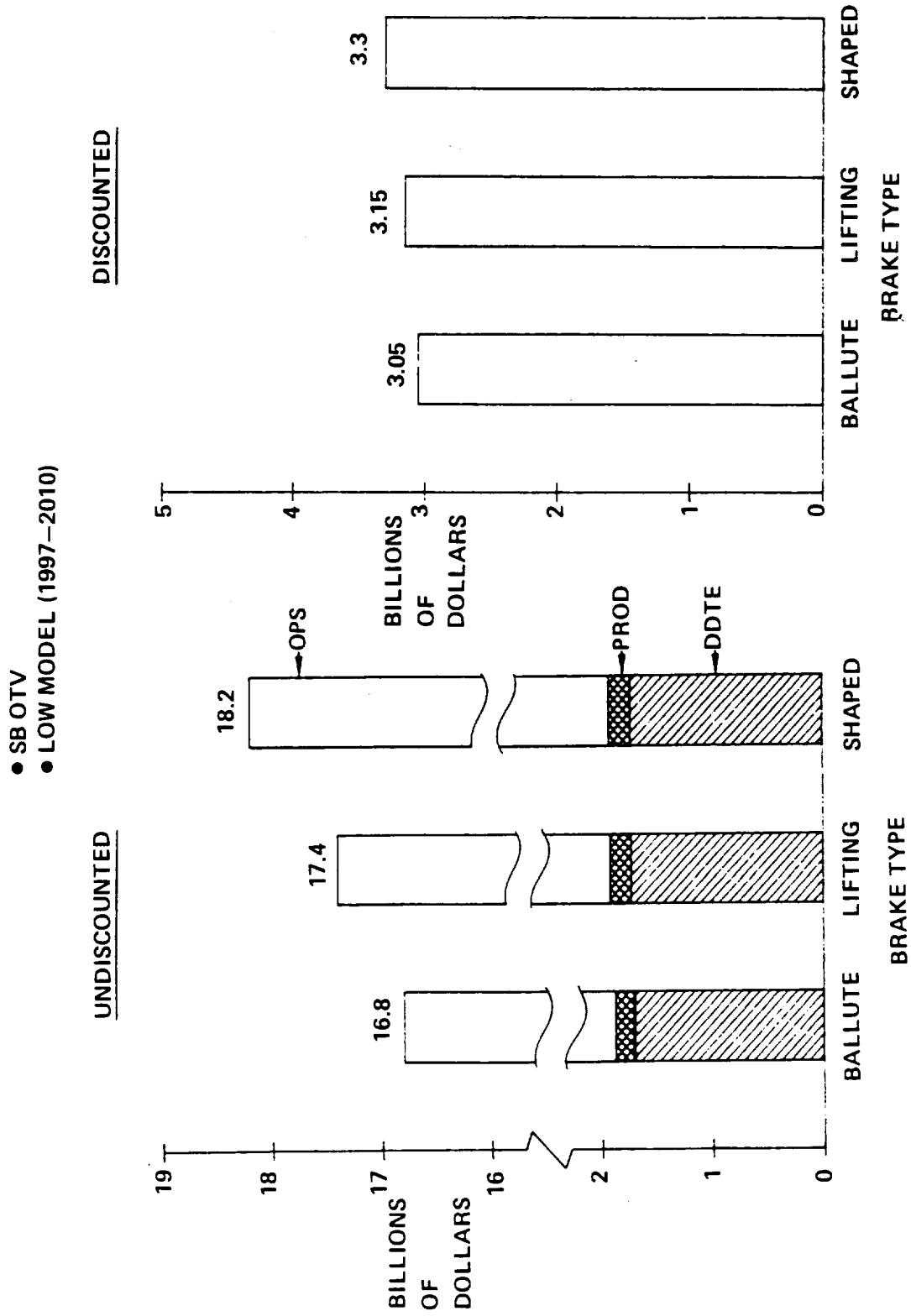
Figure 4.4.3. Aeroassist Concept Influence on OTV Program LCC

OTV-702

REFERENCE VEHICLE = 0 DOLLARS
● BALLUTE, 1500°F, T/D = 1.5
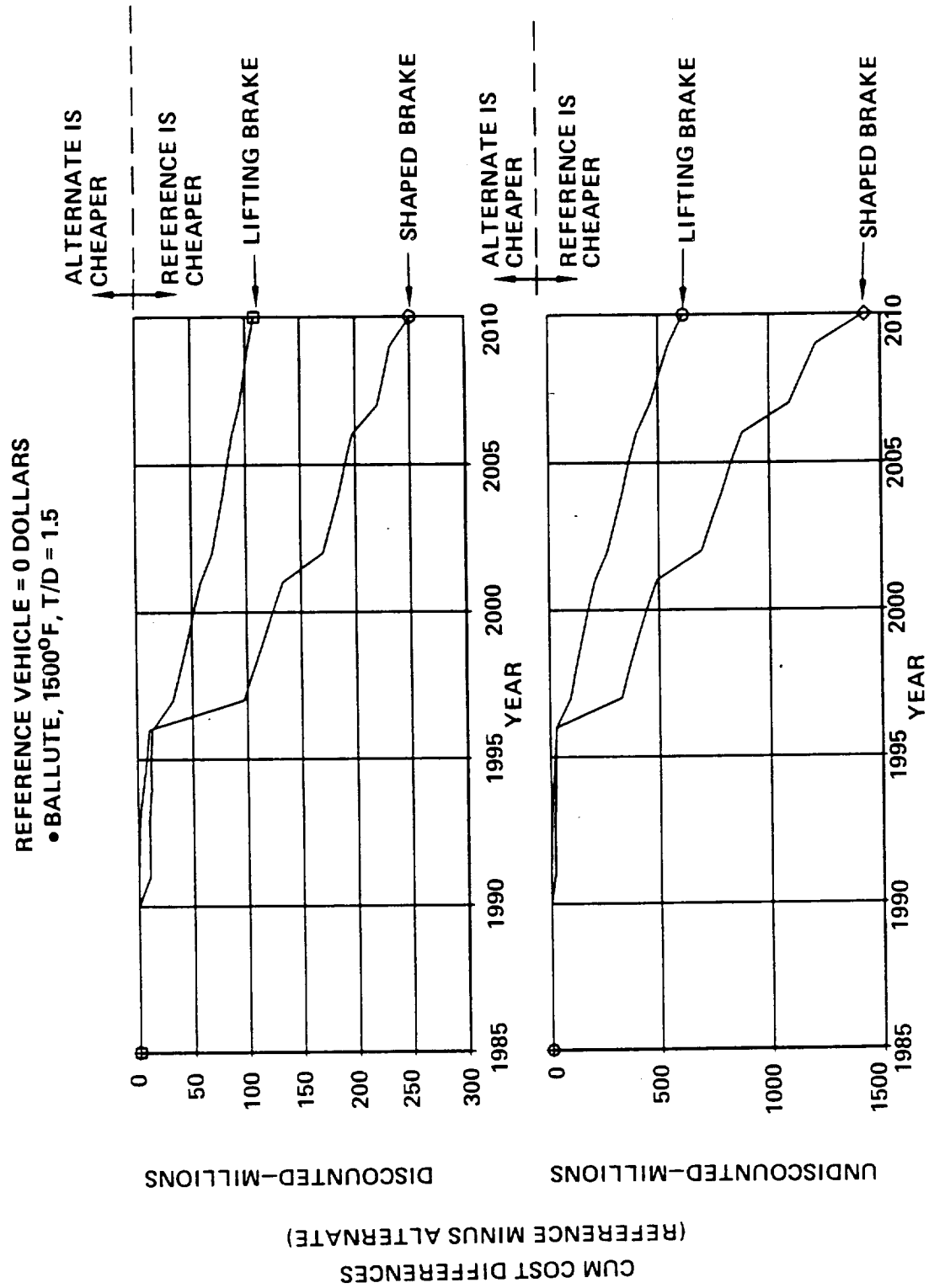
Figure 4.4.4. Time Phased LCC Comparison SB OTV Aeroassist Trade

70

OTV 840

Table 4.4-1. SB Aeroassist Assessment

- RECOMMENDATION —— BALLUTE BRAKE
  - TURNDOWN = 1.5
  - B/W = 1500°F

- LCC (UNDISCOUNTED) SAVINGS OF 3.4% AND 7.7% VERSUS LIFTING AND SHAPED BRAKE

- PAYPACK (DISCOUNTED) BEGINNING AT IOC

- PERFORMANCE ADVANTAGE MINIMIZES IMPACT OF CHANGING REQUIREMENTS

- SMALLER HANGAR AT STATION

- NO ON-ORBIT ASSEMBLY OF OTV

- MOST ADAPTABLE TO GB AND SB OTV AND CHANGE IN MISSIONS

of a small main stage and when necessary adding an auxiliary propellant tank. The characteristics of this alternative and the single stage concept are presented in figure 4.4-5. The small main stage was sized for the 12/0 K lbs GEO delivery and 11/1 K lbs multimanfest missions. These missions require approximately 45 K lbs of propellant. When more demanding missions are required, an auxiliary propellant tank is added but this does not occur until 2001. The auxiliary tank stays with the main stage throughout the mission (other auxiliary tank options are discussed in the GB OTV trades). The propellant comparison indicates that for the smaller type of missions the single stage requires more propellant because it is being flown offloaded and transporting some extra inert weight for that mission. On larger missions, the single stage is more effective than adding the auxiliary tanks to the small main stage.

The LCC comparison of the staging options shown in figure 4.4-6 indicates a small advantage for the single stage concept. This advantage occurs primarily as a result of having lower DDT&E and less operations cost associated with delivery of large GEO payloads (greater than 12 K lbs).

The time phased LCC comparison presented in figure 4.4-7 indicates the reference concept using a single stage does not become cheaper until after 2008. The reason for this late payback is that during the early years of the mission model, there are more missions of the 12 K lbs variety and those can be done more effectively by the small main stage of the main plus auxiliary propellant tank concept. As a result, it is not until there are more large missions that the single stage becomes more cost effective.

Our staging recommendation is that the baseline SB OTV should continue to be a single stage concept using LO_2/LH_2 propellant and a ballute for aeroassist. Additional characteristics associated with this concept have been shown previously in figure 4.1-9. Although this concept does not payback until quite late in the mission model it does have a lower DDT&E. In addition, this concept is less complex from an operations standpoint in that it does not require the storage or physical integration of an auxiliarly propellant tank at the Station. Finally, the single stage approach is more efficient with heavy payloads which allows for more payload growth capability which would be of particular value for the nominal model because it contains several very heavy lunar payloads.
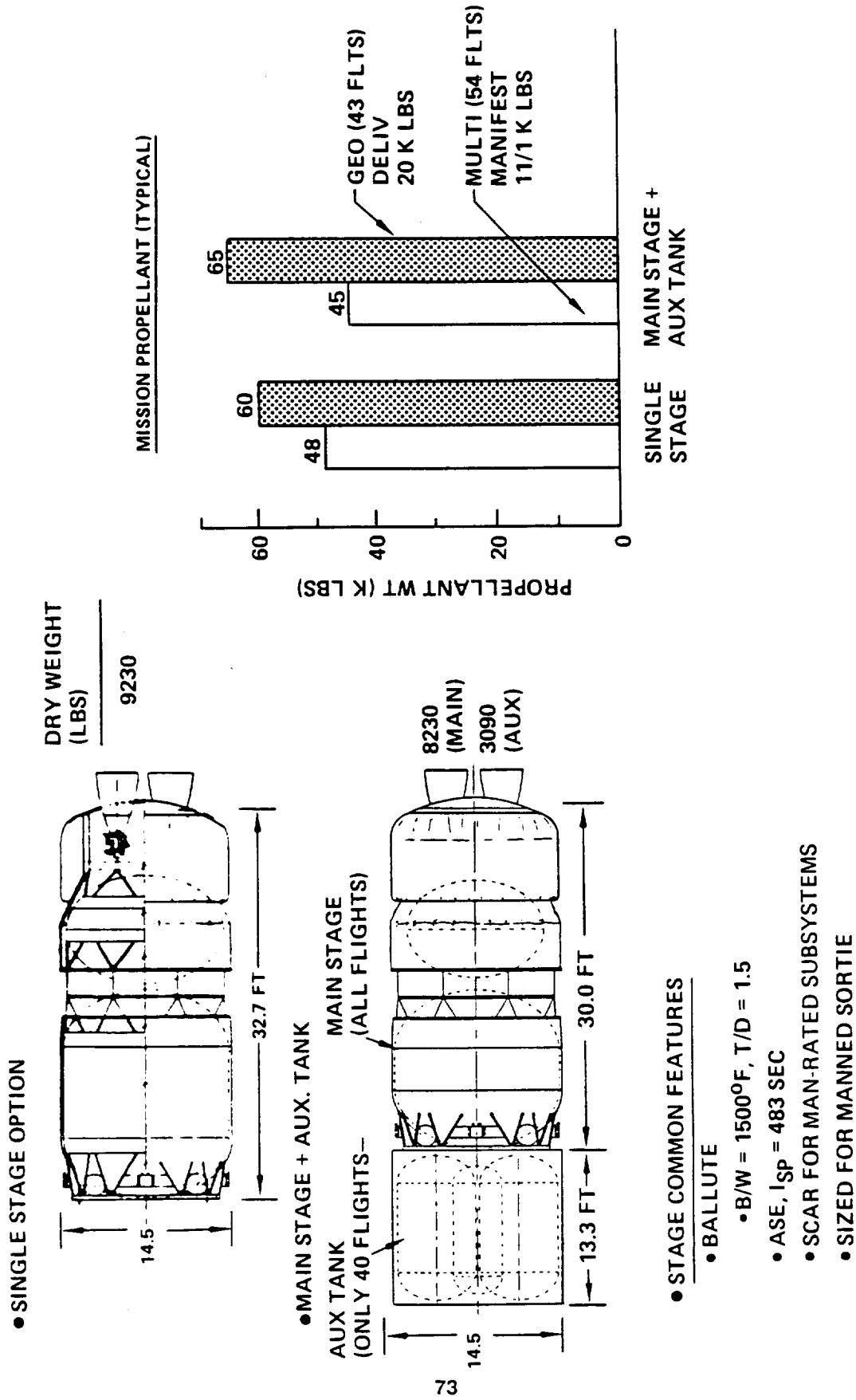
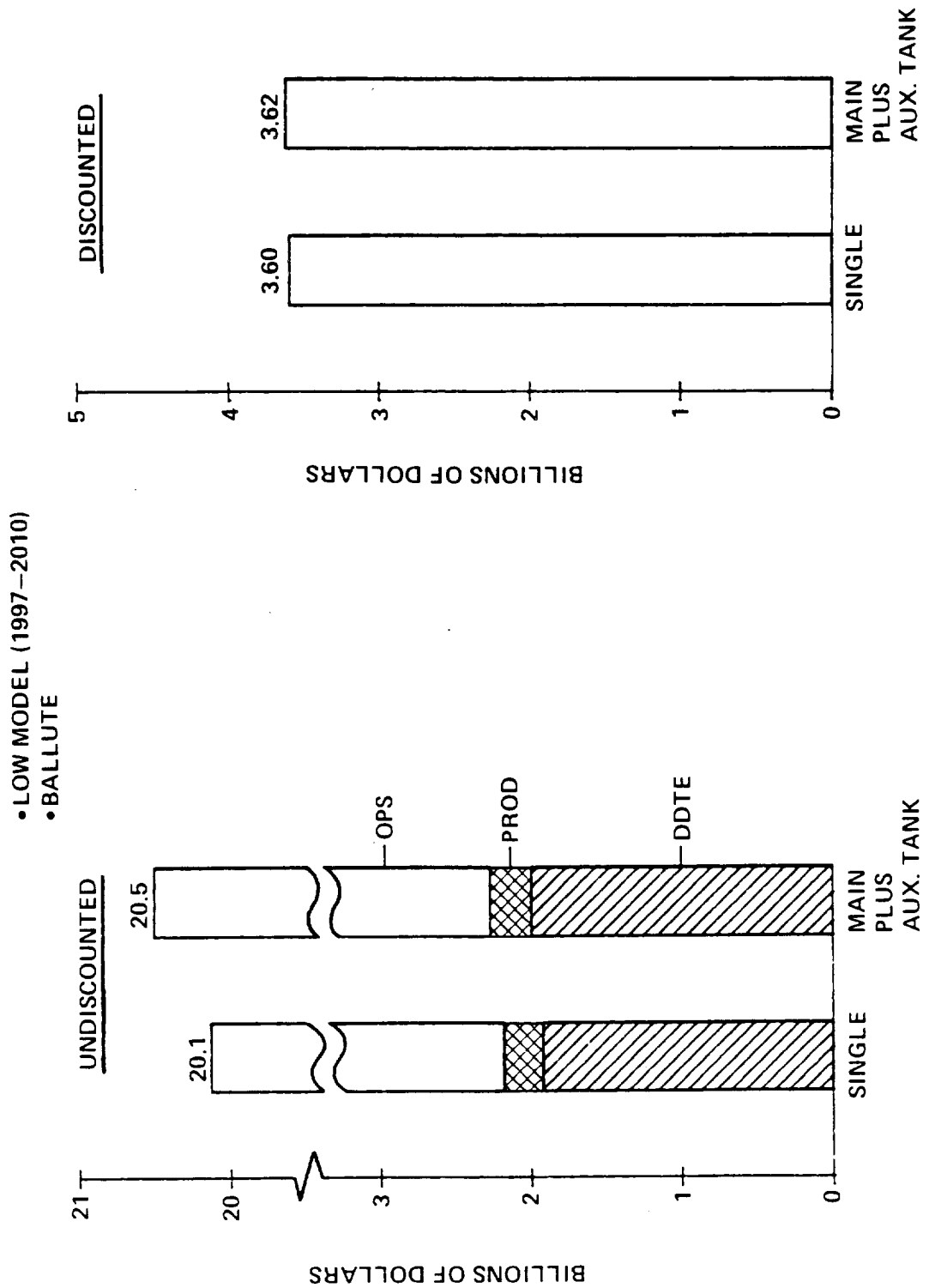Figure 4.4-5. SB OTV Staging Trade

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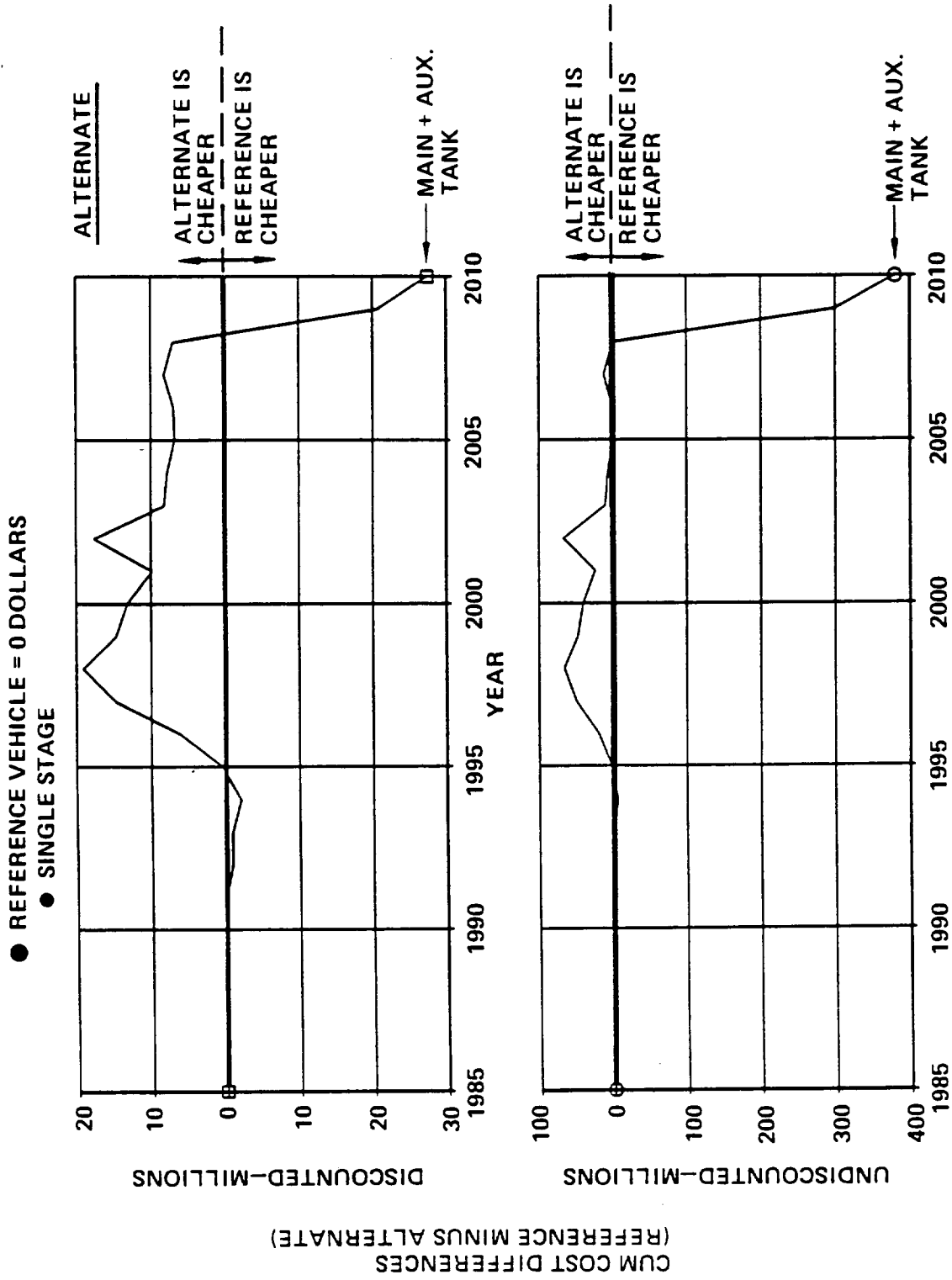Figure 4.4-6. OTV Program LCC Comparison SB OTV Staging Influence

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Figure 4.4-7. Time Phase LCC Comparison SB OTV Staging Trade

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5.0 GB OTV OPTIMIZATION TRADES

This section describes the trades conducted to achieve the optimized GB OTV. These included selection of a preferred shuttle cargo bay (SCB) OTV and aft cargo carrier (ACC) OTV and the comparison of the SCB and ACC OTV's to determine the baseline delivery mode for GB OTV. More in-depth discussion of the configurations can be found in Volume II Book 2 Section 2.0.
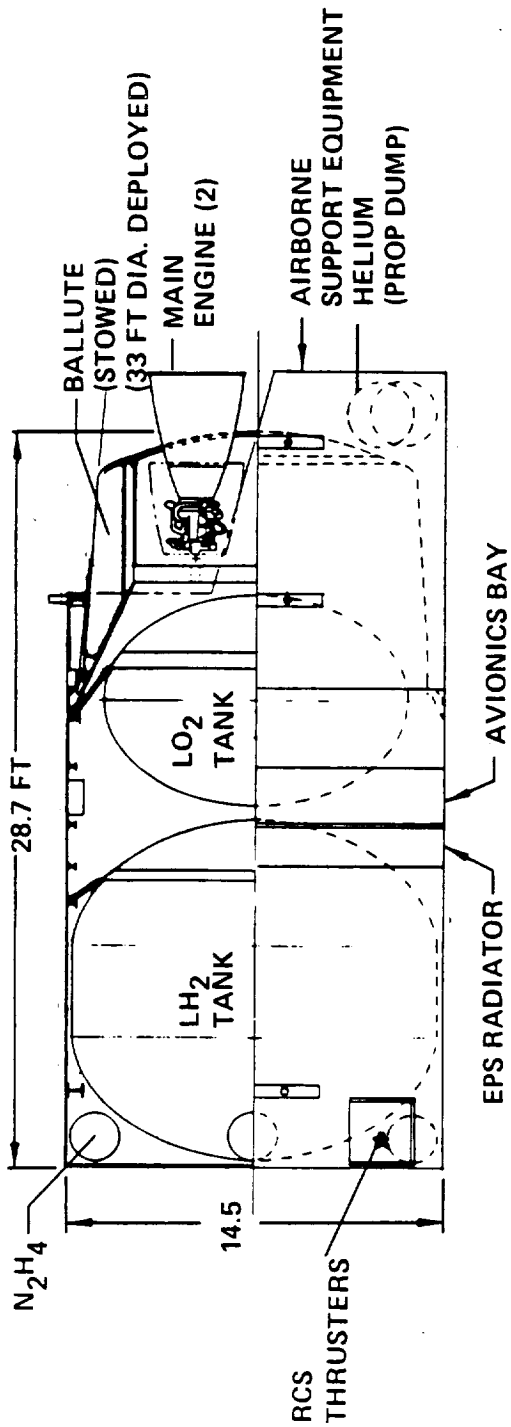
5.1 GB SCB OTV DEFINITION

This section describes the analysis performed that lead to sufficient main stage performance and selection of an auxiliary propellant tank concept.

5.1.1 Concept Description

The GB SCB OTV concept consists of a main stage used on missions involving $\leq$ 12K lbs GEO delivery or equivalent and an auxiliary propellant tankset for more demanding missions. The ground based main stage OTV is transported to orbit in the Shuttle SCB fully fueled with a payload attached. On orbit, the OTV and payload are deployed and the OTV performs its mission. Upon return to LEO, the ballute is jettisoned and the OTV is restowed in the Orbiter's payload bay for return to the ground. On the ground, the OTV is refurbished with a new ballute and is manifested for another mission. When auxiliary propellant tanks are required they are delivered along with the payload to orbit on a separate STS flight from the main stage. The main stage and auxiliary propellant tank/payload are physically integrated at the Space Station or an STS Orbiter.

5.1.2 Main Stage Performance Capability

Characteristics of the reference GB SCB OTV main stage used to conduct performance trades are presented in figure 5.1-1. Key subsystem features including use of a ballute for aeroassist are similar to those incorporated for the SB OTV as defined in Section 3.1. A major difference relative to the SB OTV is that a load carrying shell structure is used which, by its basic characteristics, provides adequate space debris and meteriod protection. The other key difference is that an IUS type tilting airborne support equipment (ASE) is used to transport a major portion of the launch loads into the orbiter. The ASE also contains a helium system that is used to expel the OTV's LO_2 and LH_2 should a launch abort occur. The reference GB OTV concept is deployed with its payload at 140 nmi and has a net delivered multimanifest payload of 8100 lbs. This

Figure 5.1-1. Reference GB OTV Main Stage

28.7 FT

14.5

N₂H₄

RCS THRUSTERS

LH₂ TANK

LO₂ TANK

EPS RADIATOR

AVIONICS BAY

BALLUTE (STOWED) (33 FT DIA. DEPLOYED)

MAIN ENGINE (2)

AIRBORNE SUPPORT EQUIPMENT

HELIUM (PROP DUMP)

KEY FEATURES

- ADV. ENGINE I_{SP} = 483 SEC
- BALLUTE B/W = 1500°F T/D = 1.5

WEIGHT SUMMARY (LBS)

• DRY	7,962
• PROP.	46,700
• OTHER FLUIDS	838
• P/L RACK	2,000
• ASE	6,390
• PAYLOAD MULTI-MANIFEST	8,110
LIFTOFF =	72,000

MAJOR CHANGES RELATIVE TO MIDTERM

- REPACKAGED BALLUTE FOR CLEARANCE WITH ASE
- MOVED RCS THRUSTERS FORWARD
- INCORP. RADIATOR FOR EPS
- INCORP. SCAR FOR MAN-RATED SUBSYSTEMS

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value is below the goal of 10,000 lbs net payload and thus further analysis was necessary.

Several options were investigated to achieve the desired payload capability. The benefits of each option are presented in table 5.1-1. A higher upper limit on engine I_{sp} offered some improvement but still well below the goal. Reducing the payload rack weight to 10% of the payload weight or assuming an expendable rack provided a substantial improvement. However to achieve the desired payload goals, the deployment altitude was decreased to 120 nmi, as well as using the reduced weight payload rack. Deployment at 120, nmi results in the orbiter having a 1 nmi per day decay rate when flying in a worst case "Y" POP attitude.

5.1.3 Auxiliary Propellant Tank Selection

More demanding missions such as manned sorties and 20,000 lb payloads will significantly exceed the capability of a main stage and a single STS launch. The additional propellant required would be provided via an auxiliary tank launched to orbit on a separate STS flight. Auxiliary propellant tank (APT) options analyzed are discussed in figure 5.1-2. The expendable APT concept consists of 2 side mounted tanks that require both to be deorbited. The recoverable concept also uses two side tanks and employs OMV to retrieve the auxiliary tanks for subsequent reuse. The integral concept uses an in-line APT which is retained during the complete mission but is removed for missions not requiring such large quantities of propellant.

The cost comparison and assessment of the auxiliary tank options investigated are presented in figure 5.1-3. Although the recovery of both APT's by the OMV on a single flight (dual-recovery) resulted in the least cost, the design scar required to allow both tanks to be jettisoned as a single unit has not been defined as yet but the weight and propellant penalty would undoubtedly have a major impact on LCC. If the tanks are jettisoned individually, the resulting trajectories most likely would necessitate single recovery or two OMV flights which significantly increased the cost. The expendable option requiring the tanks to burn upon reentry or land in an unoccupied portion of the oceans requires further analysis before this concept can be declared to be the baseline. The remaining integral concept although not the least cost does present a good compromise between cost, risk, and uncertainty and is consequently the preferred GB OTV aux. propellant tank concept.

Application of an APT for a SB OTV would have similar comparison characteristics and thus in the staging trade of section 4.4.2, an in-line APT was also used.

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Table 5.1-1.   GB Main Stage Options to Achieve Desired Payload Capability

● DESIRED SINGLE LAUNCH CAPABILITY:

   ● SINGLE PAYLOAD: 12 KLBS

   ● MULTIPLE PAYLOAD: 10 KLBS (2 IUS CLASS P/L)
     (WITH 2 KLBS REUSABLE RACK)

● OPTIONS AND CAPABILITIES

PARAMETER	REFERENCE VEHICLE	OPTION 1	OPTION 2	OPTION 3
● MPS I_{SP} (SEC)	483	488	√	√
● PAYLOAD RACK WEIGHT (LBS)	2000	√	1000 [1] 2000 [2]	1000 [1] 2000 [2]
● START/END ALTITUDE (NMI)	140/150	√	√	120/150
● PAYLOAD CAPABILITY (LB)				
● MULTIPLE	8100	8450	9750	10,425
● SINGLE	11385	11715		12,065

√ MEANS SAME AS REFERENCE

[1] REUSABLE   [2] EXPENDABLE

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REQUIREMENT: 20K LB PAYLOADS; MANNED SORTIE

OPTIONS FOR AUXILIARY PROPELLANT TANK

① EXPENDABLE   ② RECOVERABLE   ③ INTEGRAL

MAIN STAGE

AUX. TANK

AUX. TANKS
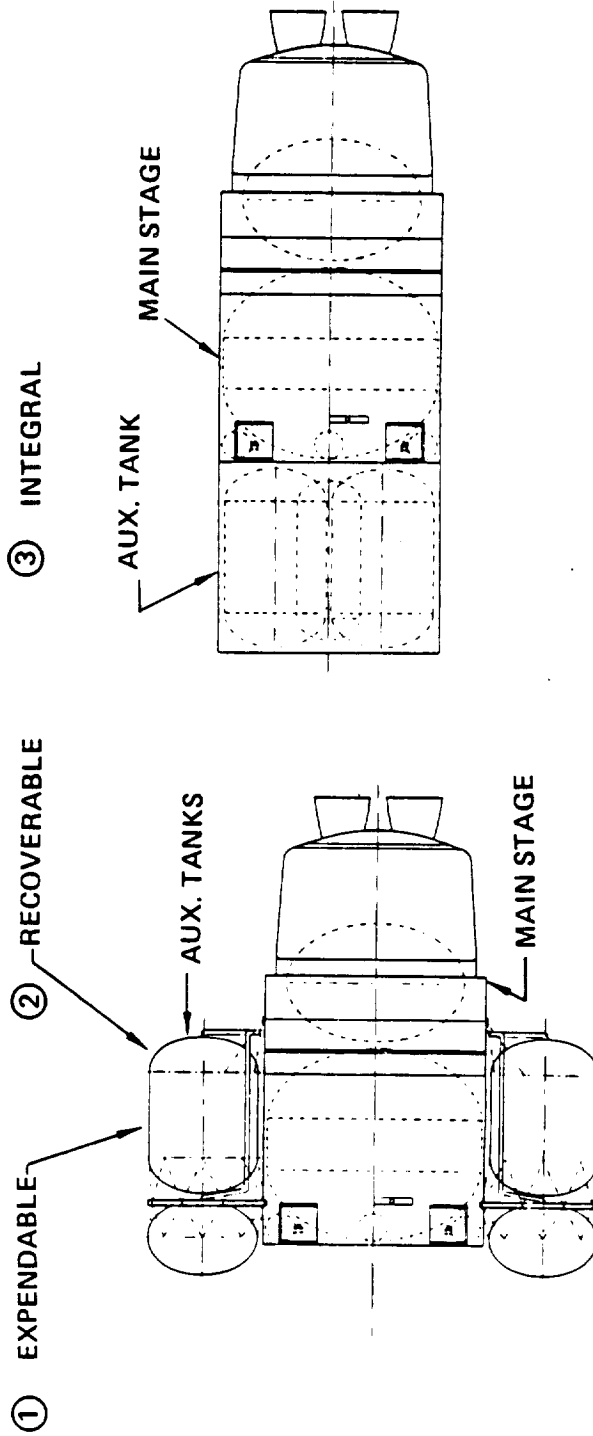
MAIN STAGE

BASIC OPERATIONS

①. AUX TANK/PAYLOAD TO STATION
②. MAIN STAGE POWERED FLIGHT
    TO STATION

③ ELEMENTS INTEGRATED AT STATION
④. PERFORM MISSION
⑤. STAGE RETURNS TO ORBITER

AUX. TANK OPERATIONS

• EXPENDABLE
  • JETTISON AFTER BURN NO. 1.
  • DEORBIT WITH ON BOARD EQUIP.

• RECOVERABLE
  • JETTISON AFTER BURN NO. 1
  • OMV RECOVERS TANKS

• INTEGRAL
  • TANK REMAINS WITH STAGE
    THROUGHOUT MISSION

Figure 5.1-2. GB OTV Auxiliary Propellant Tank Options

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Figure 5.1-3. Auxiliary Tank Comparison GB OTV

5.1.4 Selected GB SCB Ballute Braked OTV

The selected GB SCB OTV resulting from the optimization studies is shown in figure 5.1-4. Features generally relating to the ballute and heat shield are the same as for the SB ballute braked OTV. The main stage of this concept is used by itself on 109 of 145 missions and deploys directly from the Orbite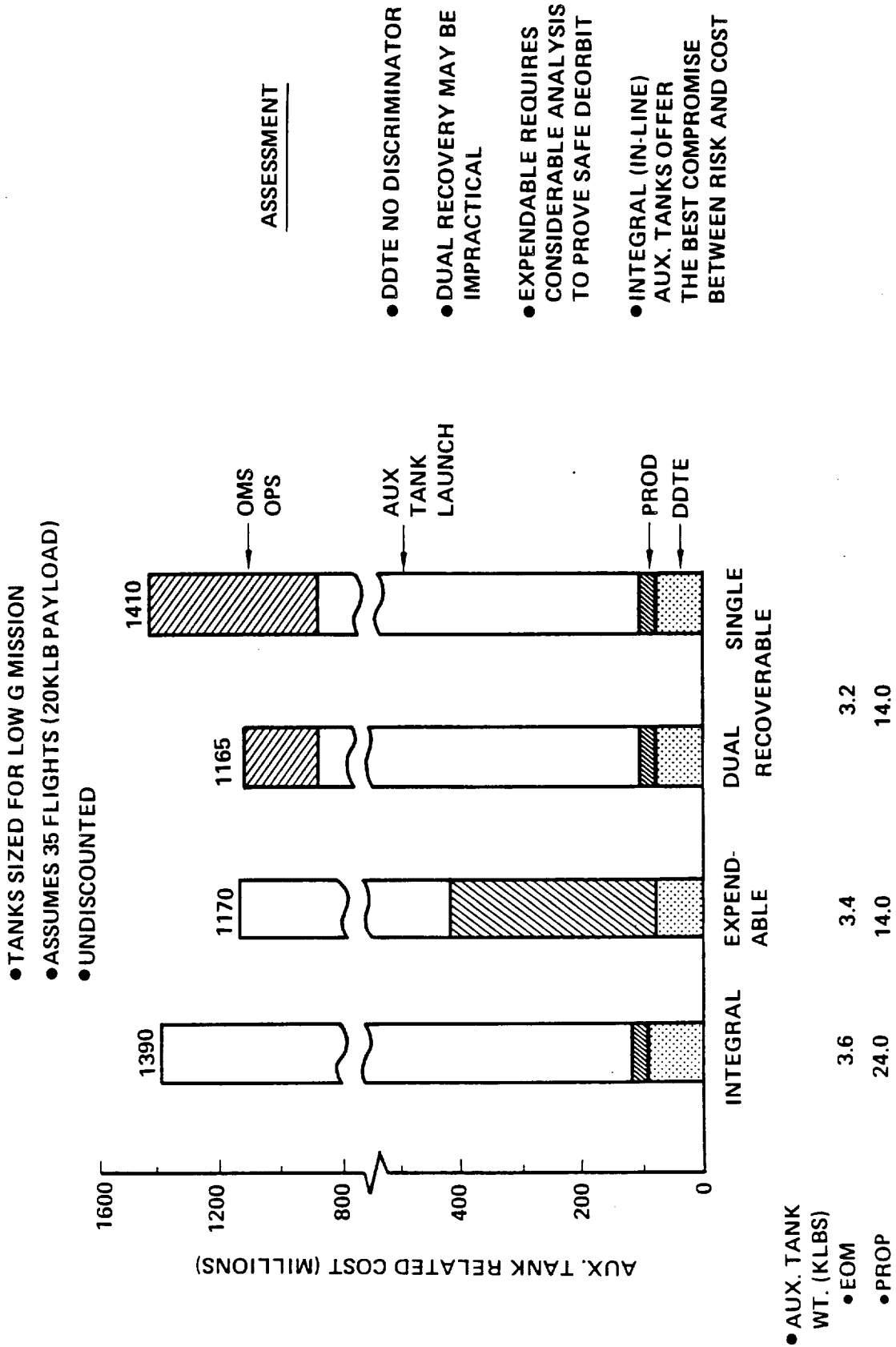r. For more demanding missions involving 20,000 lb GEO deliveries or manned GEO sorties, an auxiliary propellant tank is added and remains with the stage throughout the flight. On these flights (36) the auxiliary tank/payload combination is delivered to the station followed by delivery of the main stage. The role of the station is to ensure the physical integration of the elements prior to the mission. The stage starburn weight for multimanifest or 12,000 lb delivery missions is 56,461 lbs. and for manned GEO sortie missions the main stage plus auxiliary tank weights 96,508 lbs.

5.2 GB ACC OTV DEFINITION

This section describes the concept and configuration for the ACC OTV.

5.2.1 Concept Description

This concept also involves use of a main stage and auxiliary propellant tank. The ground-based ACC OTV main stage employs a symmetrical lifting brake and is launched in the Aft Cargo Carrier. For missions involving $\leq$8.4K lbm, the payload is launched in the Shuttle Orbiter cargo bay. On orbit, the OTV and payload are mated, and the mission is performed similar to other ground-based OTV concepts. After the main stage returns to LEO, the lifting brake is jettisoned and the vehicle is disassembled and stowed in the Orbiter for the return to the ground. On the ground, the OTV is refurbished and reassembled, then integrated into the ET ACC for re-launch. For payloads $\geq$8.4K-lbm, an auxiliary propellant tank is required and is launched along with payload in the Orbiter cargo bay. Again, on-orbit assembly of the main stage and auxiliary tank/payload are required.

5.2.2 Configuration Description

A description of the configuration including weights and earth return configuration follows.

Main Stage—No. 107. The deployed flight configuration for the four tank concept is shown in figure 5.2-1. The concept employs (2) advanced cryogenic engines, (2) LO_2 tanks, (2) LH_2 tanks, an avionics equipment section and a deployed symmetrical lifting

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BALLUTE DEPLOYED

DIAMETER
- MAIN STG ONLY = 33 FT
- MAIN STG & AUX TANK + MAN P/L = 65 FT

WEIGHT SUMMARY (LBS)

	10K NET DELIV	MANNED SORTIE (7.5K)	
	MAIN	MAIN	AUX
DRY	7995	9987	3401
MAIN PROP	47698	47698	33722
OTHER FLUIDS	768	1700	—
STG STARTBURN	56461	59385	37123
PAYLOAD (NET)	10000	—	7500
PAYLOAD RACK	1000	—	—
ASE	6390	6390	6390
LIFTOFF	73851	65775	51013
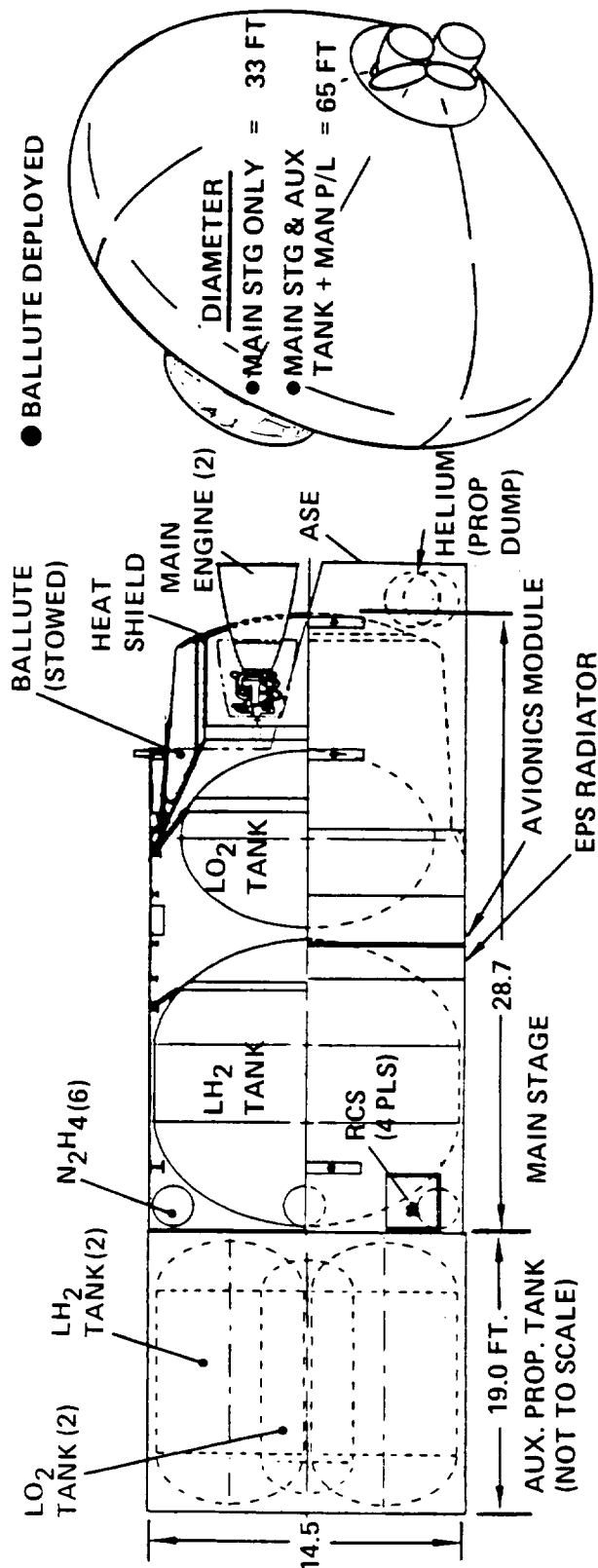
UNIQUE FEATURES

- BALLUTE—SAME AS SB OTV

- HEAT SHIELD—SAME AS SB OTV

- MAIN STAGE
  - USED ON ALL FLIGHTS

- AUX. PROP. TANK
  - USED ON 36 FLIGHTS

- MAIN STAGE ATTACHED TO AUX. TANK/PAYLOAD AT STATION

Figure 5.1-4. GB Ballute Braked OTV

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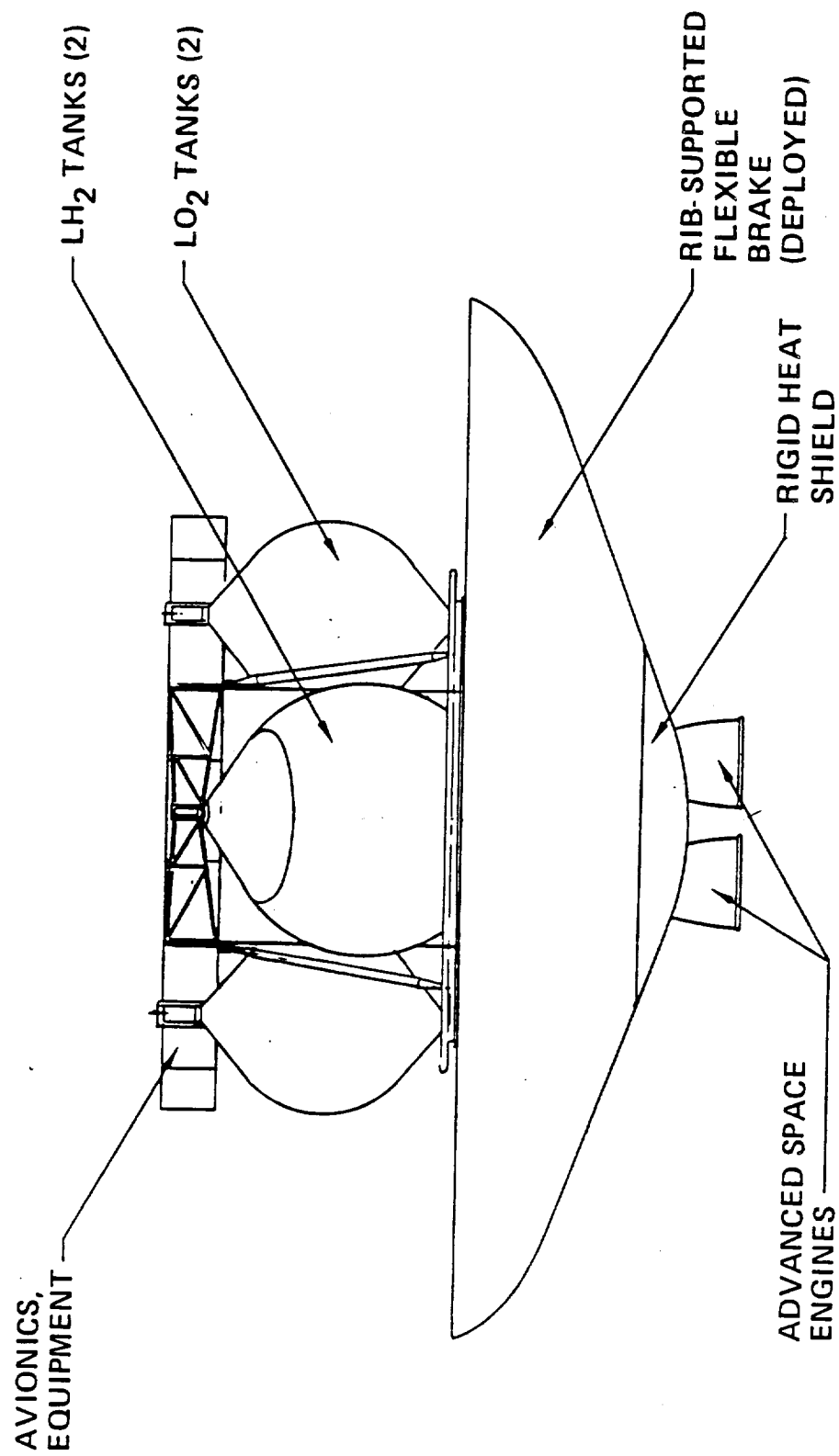
Figure 5.2-1 GB ACC OTV No. 107 Configuration

LH₂ TANKS (2)

LO₂ TANKS (2)

RIB-SUPPORTED FLEXIBLE BRAKE (DEPLOYED)

RIGID HEAT SHIELD

AVIONICS, EQUIPMENT

ADVANCED SPACE ENGINES

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brake. A ballute was not considered for this concept because the short body of the vehicle does not allow for proper attachment (distance between fore and aft attachment points should be approximately 0.5 the radius of the ballute).
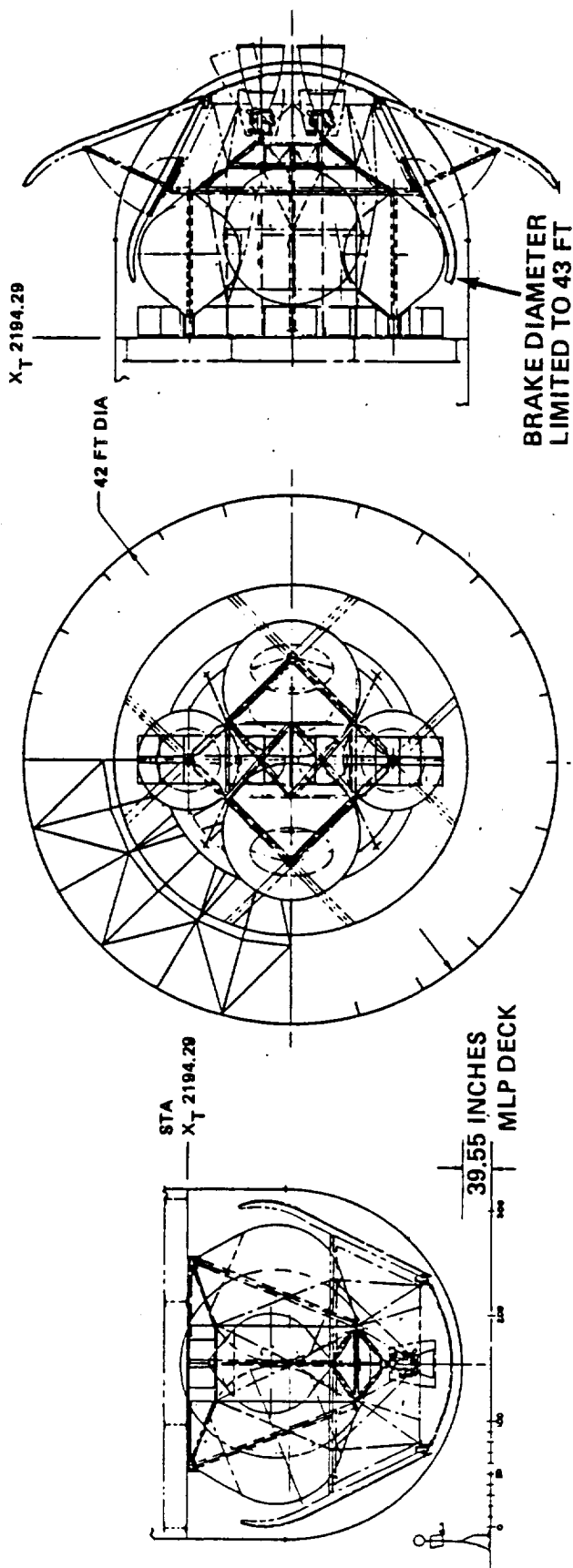
Further configuration characteristics and a weight summary is presented in figure 5.2-2. The ACC employed is a stretched version that allows the maximum length OTV. The ACC is attached to the aft end of the shuttle's external tank. As such, only a 40 inch clearance exists between the ACC and MLP deck. The other key aspect is that the brake is limited to a diameter of 43 ft due to stowage constraints. This is adequate for main stage delivery missions however for missions using an auxiliary propellant tank a diameter of 60 ft (for manned missions) would be required (assuming the same wake heating impingement angle used for the SCB ballute concept---22 deg plus 10 deg for angle of attack when using the lifting brake). Obviously, the 60 ft brake cannot be incorporated within the ACC. The weight for this size would add an additional 1700 lbm of dry weight resulting in an extra 5000 lbm of propellant. For the purposes of performing the SCB versus ACC OTV trade this shortfall in ACC brake diameter was ignored.

The main stage system is capable of delivering 8.4K lbm to GEO.

Auxiliary Propellant Tanks. For missions requiring more than 8.4K-lbm, auxiliary propellant tanks must be included. One size provided 13.8K-lbm of propellant for 12K-lbm payload delivery missions. Another tankset shown in figure 5.2-3 provided 30.8K lbm of propellant for missions involving 20K-lbm payload or 7.5K-lbm manned round trips.

Return Configuration. The Earth return configuration for this OTV is shown in figure 5.2-4. The vehicle is disassembled on-orbit into four major elements: (2) LH_2 tanks, LO_2 tanks/avionics section, and main engine compartment. The lifting brake is always expended as is an auxiliary tank (should it be required) because there is not sufficient space in the cargo bay.

Weight Summary. The launch weight summary for this concept as it relates to the major mission categories is shown in table 5.2-1. It should be noted that the ASE weight relates to that equipment/systems necessary to launch a payload and to enable the ACC OTV to be disassembled on-orbit and support in the cargo bay for return to Earth. The ACC weight is the effective weight penalty as a result of staging this unit during the

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X_T 2194.29

42 FT DIA

BRAKE DIAMETER
LIMITED TO 43 FT

STA
X_T 2194.29

39.55 INCHES
MLP DECK

WEIGHT SUMMARY (LBM)

	MAN RATED	MAN SCAR ONLY
● DRY	8,430	8,179
● MAIN PROP. (TOTAL)	42,630	42,630
● OTHER FLUIDS	1,169	1,169
● START BURN	52,229	51,978

FEATURES:

● LAUNCHED IN ET-OCB
● RETURNED IN STS-OCB
● LIFTING BRAKE AEROASSIST,
  −EXPENDABLE
● ADVANCED CRYO ENGINE T=5000 LBF
● 4 TANKS
● PROPULSION/HEATSHIELD MODULE

Figure 5.2.2 GB ACC OTV Concept 107 Configuration

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180" SCB DYNAMIC ENVELOPE

219 IN

LH₂
VOL = 1052 FT3

121.59 IN

LO₂
VOL = 379.8 FT3

85.56 IN

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WEIGHT SUMMARY (LBM)

● USABLE PROPELLANT,   30,000

● INERT   3,220
                          _____
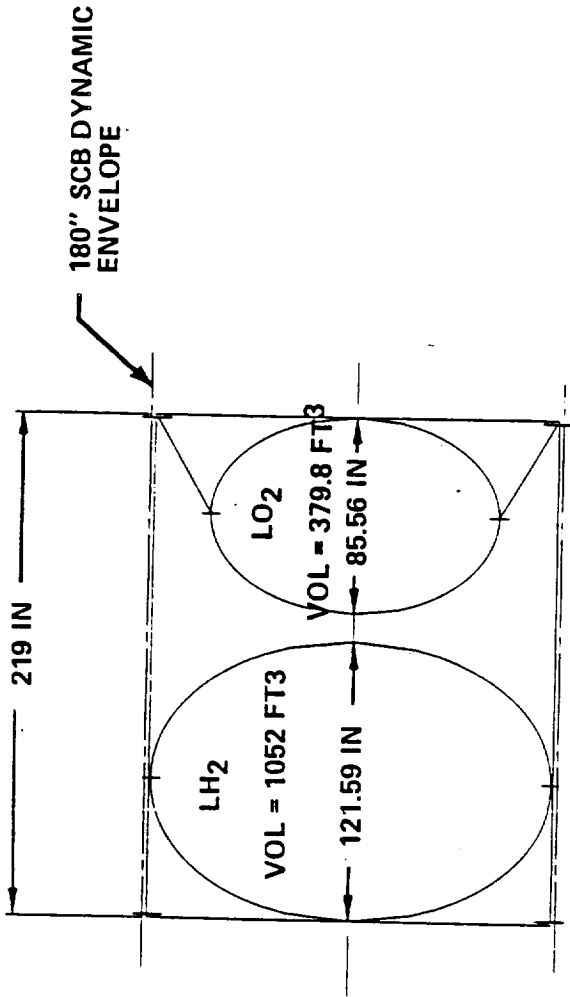
● TOTAL   34,020

FEATURES

● ONE LH₂ TANK 0.707 ELLIPTICAL HEADS

● ONE LO₂ TANK 0.707 ELLIPTICAL HEADS

● OCB–CARRIED THRU 4 TRUNNIONS AND
  ONE KEEL PIN

Figure 5.2-3 30.8K Auxiliary Tank GB SCB OTV

ENGINE MODULE

CORE

LH₂ TANK (2)

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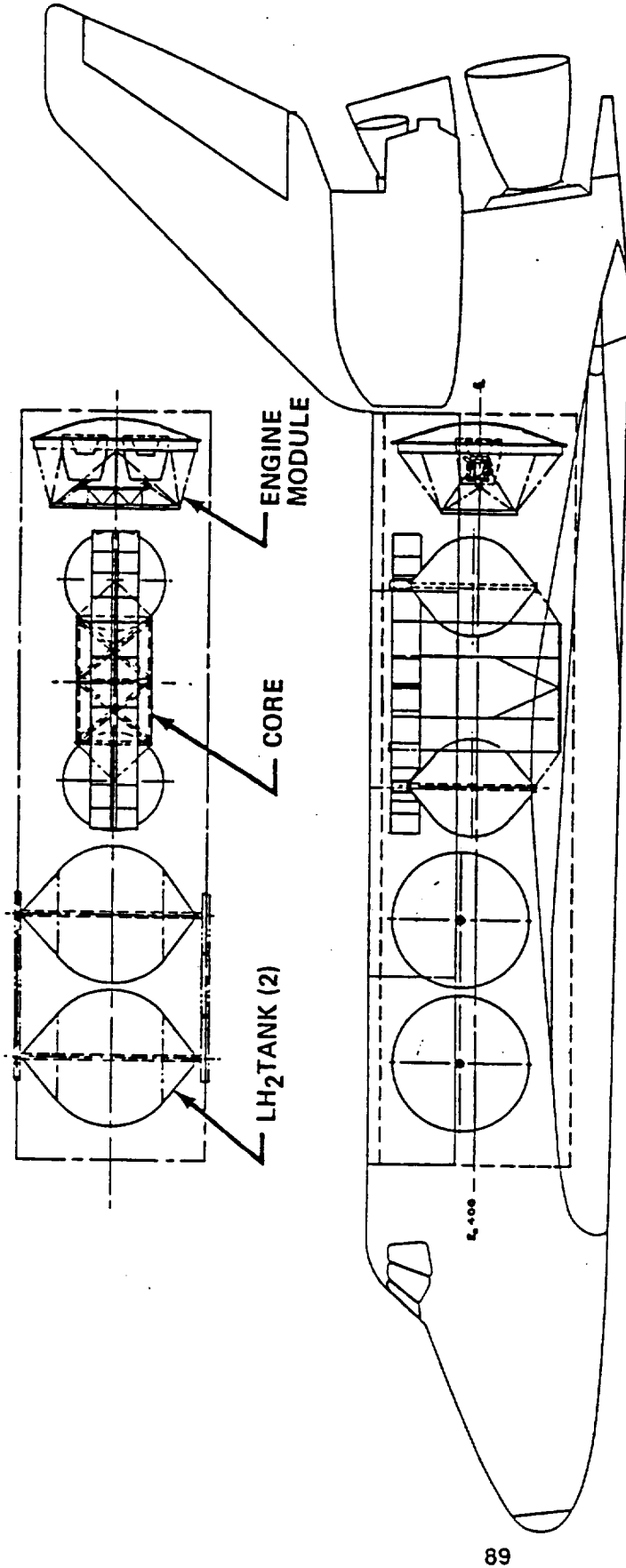
FEATURES

- TWO LH TANKS MOUNTED FORWARD
- VEHICLE BUSS WITH AVIONICS AND TWO LO₂ TANKS
- MODULE CONTAINING TWO ENGINES AND HEATSHIELD
- ALL TRUNNION MOUNTED AT BRIDGERAIL FITTINGS TO LONGERONS
- ASE WEIGHT FOR STAGE AND PAYLOAD---6760 LBS

Figure 5.24 GB ACC OTV No. 107 Return Configuration

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Table 5.2-1 GB ACC Concept No. 107 Weight Summary (LB)

	5.3K GEO DELIV. △1	8.4K GEO DELIV.	12K GEO DELIV.	20K GEO DELIV.	7.5K MANNED ROUND-TRIP
STAGE DRY WEIGHT △3	8,179	8179	8,179	△4 8,179	8,430 △5
AUX. TANK DRY WEIGHT	—	—	2,395	2,990	2,990
TOTAL MPS PROPELLANT	38,810	43,040	57,010	73,855	75,455
OTHER FLUIDS	950	781	1,000	1,330	1,209
PAYLOAD △3	5,300	8,420	12,000	△4 20,000	7,500 △5
START-BURN WEIGHT	53,239	60,420	80,584	106,354	95,584
ASE	6,761	6,761	△2 10,409	△2 10,409	△2 10,409
ACC	5,000	5,000	5,000	5,000	5,000
TOTAL LAUNCH WEIGHT	65,000	72,181	95,993	121,763	110,993

△1 65K STS LIMIT SIZING
△2 REFLECTS ASE FOR TWO STS LAUNCHES (1ST-P/L + AUX. TANK; 2ND-STAGE
△3 REFLECTS MAX. BRAKE SIZE IN ACC
△4 IF BAC BRAKE REQ'T SATISFIED: BRAKE WT + 870 LBS; PAYLOAD -870 LBS
△5 IF BAC BRAKE REQ'T SATISFIED: BRAKE WT + 1500 LBS; PAYLOAD -1500 LBS

launch. A final point is that weights for any mission beyond 8.4k lbm GEO delivery equivalent reflect two STS launches.

5.3 DELIVERY MODE SELECTION
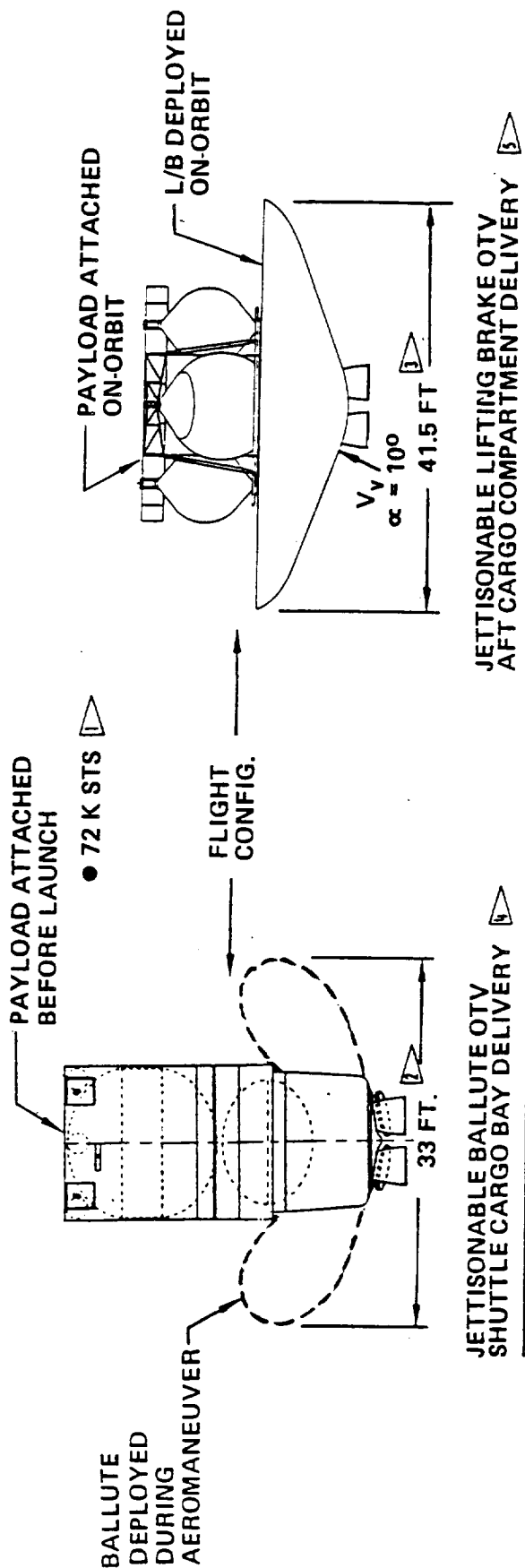
5.3.1 Concept Summary

The key features of the two GB OTV delivery modes are summarized in figure 5.3-1. For the case of using only the main stage (a single STS flight) the SCB concept allows nearly 1200 lbm of additional payload. The major contributor to this advantage is that the ACC OTV requires significantly more weight in the areas of ASE plus ACC. This occurs because the ASE for launching the SCB OTV/payload is adequate to return the OTV. In the case of the ACC OTV, the ACC is required to support the OTV during launch and additional ASE is necessary in the cargo bay to support the payload and to enable the OTV to be returned. In addition, over 1000 lbm of the dry weight difference relates to the ballute being more efficient than the symmetrical lifting brake. It should also be remembered that the ACC OTV lifting brake diameter is limited to 43 ft and a number of missions require diameters of 53 ft and 60 ft. Consequently, to accommodate these diameters a major redesign of the main stage would be required resulting in significant weight penalties. However for this delivery mode comparison the larger brake diameter impact will be ignored.

5.3.2 Launch and Recovery Operations

STS flight operations in terms of launch and recovery for the SCB and ACC OTV's is presented in tables 5.3-1 and 5.3-2, respectively. This data identifies the number of missions requiring one or two STS flights and the resulting users charge load factor. A full load factor (1.0) occurs when either the weight or length of the cargo reaches three quarters of the capacity.

In the case of the SCB OTV concept (table 5.3-1) 65 missions require a single STS flight while 80 need two STS flights. It should be noted that on high inclination missions the load factor is due to length requirements. For the ACC OTV operations shown in table 5.3-2, 13 additional flights are required for class 1 missions because of reduced OTV payload capability for this concept when using a single STS flight. Reduced OTV payload capability also contributed to two additional missions requiring two STS flights per mission.

Related to the STS flight operations are the specific OTV operations associated with launch and recovery. In this regard, the ACC OTV has a number of unique

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PAYLOAD ATTACHED ON-ORBIT

L/B DEPLOYED ON-ORBIT

V_v
$\alpha \approx 10°$

41.5 FT

JETTISONABLE LIFTING BRAKE OTV
AFT CARGO COMPARTMENT DELIVERY △5

PAYLOAD ATTACHED BEFORE LAUNCH

● 72 K STS △1

FLIGHT CONFIG.

33 FT.

JETTISONABLE BALLUTE OTV
SHUTTLE CARGO BAY DELIVERY △4

BALLUTE DEPLOYED DURING AEROMANEUVER

	SCB/JETT. BALLUTE	ACC/JETT. LIFTING BRAKE
● DRY WT (LBS)	7,961	8,179
(JETTS. AERO. DEVICE)	(930)	(2014)
● TOTAL MPS PROPELLANT	46,790	43,314
● OTHER FLUIDS	758	812
● PAYLOAD	10,000	7,834
● RACK	1,000	1,000
● ACC (EFFECTIVE WT.)	—	5,000
● ASE	6,391	6,761
LIFTOFF	72,900	72,900

△1 CAPABILITY AT 120 NM IS 73,500 LB
△2 SIZED BY TURN-DOWN RATIO STABILITY–PROVIDE >22° WAKE IMPINGEMENT ANGLE
△3 SIZED BY 22° WAKE IMPINGEMENT ANGLE–THIS IS ALSO MAX DIA CAPABLE IN ACC
△4 BALLUTE LESS WEIGHT THAN LIFTING BRAKE FOR SCB OTV
△5 BALLUTE CANNOT BE ADEQUATELY ATTACHED TO ACC OTV
△6 BOTH CONCEPTS USE ADV. LO$_2$/LH$_2$ ENGINE

Figure 5.3-1 Ground Based OTV Options

Table 5.3-1 GB SCB OTV Launch and Recovery Operations

● 72K STS

MISSION CLASS	NUMBER FLIGHTS (GEO/HI INCL)	FLIGHT OPERATIONS	USERS CHARGE LOAD FACTOR △	
			GEO	HI INCL
① GEO 12/0 AND 11/1 KLBS ≤ 25FT	65	● STS 1 – MAIN STAGE + RASE + PAYLOAD TO DEPLOYMENT ORBIT ● OTV RETURNS TO STS 1	1.0 (W)	—
② DOD 12/0 KLBS 30 FT	28 (17/11)	● STS 2 – MAIN STAGE + RASE ● STS 1 – PAYLOAD + ASE ● OTV RETURNS TO STS 2	1.0(W) 0.73(L)	0.69(L) 0.73(L)
③ DOD 20 KLBS 35 FT	40 (24/16)	● STS 2 – MAIN STAGE + RASE ● STS 1 – AUX TANK + PAYLOAD + ASE △ ● OTV RETURNS TO STS 2	1.0(W) 1.0(W)	0.76(W) 0.77(L)
④ GEO 20 KLBS 35 FT	9	● STS 1 – AUX TANK + PAYLOAD + ASE ● STS 2 – MAIN STAGE + RASE ● OTV ELEMENTS INTEGRATED AT STATION ● OTV RETURNS TO STS 2	1.0(W) 1.0(W)	— —
⑤ GEO MAN SORTIE 7.5K/10 FT	3	● STS 1 – AUX TANK + PAYLOAD + ASE ● STS 2 – MAIN STAGE + RASE ● OTV ELEMENTS INTEGRATED AT STATION	1.0(W) 0.77(W)	— —
	145			

RASE = RETURN AIRBORNE SUPPORT EQUIP
△ COST CRITERIA: (W) WEIGHT; (L) LENGTH ;1.0 = FULL CHARGE =$73M
△ AUX TANK ONLY ON GEO MISSIONS

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Table 5.3-2 GB ACC OTV Launch and Recovery Operations

● 72 K STS

MISSION CLASS	NUMBER FLIGHTS (GEO/HI INCL)	FLIGHT OPERATIONS	USERS CHARGE LOAD FACTOR	
			GEO	HI INCL
① GEO 12/0 AND 11/1 KLBS ≤ 25 FT	78	● STS 1 – MAIN STAGE + ACC + PAYLOAD + ASE TO DEPLOYMENT ORBIT ● OTV RETURNS TO STS 1	1.0(W)	—
② DOD 12/0 KLBS 30 FT	30 (18/12)	● STS 2 – MAIN STAGE + RASE + ACC ● STS 1 – PAYLOAD + AUX. TANK + ASE ● OTV RETURNS TO STS 2	1.0(W) 0.87(L)	0.96(W) △2 —
③ DOD 20 KLBS 35 FT	40 (24/16)	● STS 2 – MAIN STAGE + RASE + ACC ● STS 1 – AUX. TANK + PAYLOAD + ASE ● OTV RETURNS TO STS 2	1.0(W) 1.0(W)	0.9(W) 0.77(L)
④ GEO 20 KLBS 35 FT	9	● STS 1 – AUX. TANK + PAYLOAD + ASE ● STS 2 – MAIN STAGE + ACC + RASE ● OTV ELEMENTS INTEGRATED AT STATION ● OTV RETURNS TO STS 2	1.0(W) 1.0(W)	— —
⑤ GEO MAN SORTIE 7.5K/10 FT	3 ――― 160	● STS 1 – AUX. TANK + PAYLOAD ● STS 2 – MAIN STAGE + ACC + RASE ● OTV ELEMENTS INTEGRATED AT STATION	1.0(W) 0.77(W)	— —

RASE = RETURN AIRBORNE SUPPORT EQUIPMENT

△1 COST CRITERIA: (W) WEIGHT; (L) LENGTH

1.0 = FULL CHARGE = $73M

△2 INCLUDES PAYLOAD

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operations relative to the SCB OTV. A summary of these operations is presented in table 5.3-3 for the case of a mission involving a single STS flight. Several unique operations must occur before the primary OTV mission begins. These include the ACC OTV separating from the Shuttle during the launch or in a low parking orbit and then the OTV making a powered flight to a higher parking orbit where rendezvous and docking occurs with the Orbiter. At this point the ACC OTV and payload must be physically mated and an integrated system level checkout performed. These assembly/checkout operations have been timelined and result in 11 IVA crew hours and 10 EVA crew hours. After the ACC OTV completes its mission and returns to LEO it must be disassembled so the elements can fit into the Orbiter's cargo bay (in the launch configuration, the OTV is 25 ft in diameter). These operations and stowed configuration were previously discussed in section 5.2. Timelines have indicated 15 IVA crew hours and 20 EVA crew hours are involved.

5.3.3 Life Cycle Cost (LCC) Comparison

The LCC comparison of the two OTV concepts performing the Rev 8 low mission model is presented in figure 5.3-2. A $2.5 billion advantage occurs for the SCB concept primarily due to the savings in operations cost. With 10% discounting the SCB provides a 13% advantage.

A breakdown of the LCC in terms of specific differences in DDT&E, production and operations cost is presented in table 5.3-4. The most significant DDT&E difference is that the ACC OTV concept requires development of the light weight aft cargo carrier (LWACC) that is used to support the OTV during launch. In the area of production cost, the major difference is that the ACC OTV's auxiliary propellant tank cannot be reused because there is no space available in the cargo bay for its return (the bay is filled with main stage elements). Operations cost show approximately a $2 billion advantage for the SCB OTV. The advantage in launch cost ($73 million for full launch) relates primarily to fewer launches because of better OTV payload capability and to a lesser degree lower load factors. The SCB also has less expendable hardware (no ACC and the ballute is cheaper than the lifting brake). Finally, in the area of on-orbit operations, the SCB has a significant cost advantage because on orbit assembly only occurs on 80 flights whereas it occurs on all flights (160) for the ACC OTV, but most significantly every flight (160) of the latter also requires disassembly before the vehicle can be returned to Earth. Study groundrules at the time of this comparison included a cost of $75,000 per EVA crew hour and $17,000 per IVA crew hour.

Table 5.3-3 ACC OTV Unique Operations

ON-ORBIT

- POWERED FLIGHT TO PARKING/ASSEMBLY ORBIT

- OTV/PAYLOAD MATING AND CHECKOUT

  - TWO RMS'S
  - 11 IVA CREW HOURS (INCL PREP.)
  - 10 EVA CREW HOURS

- OTV DISASSEMBLY FOR EARTH RETURN

  - REMOVE 2 LH$_2$ TANKS
  - REMOVE ENGINE COMPARTMENT
  - STOW CORE MODULE
  - 15 IVA CREW HOURS (INCL PREP)
  - 20 EVA CREW HOURS

- GROUND (RELATIVE TO SCB)

  - REMOVAL/TRANSPORTING 4 UNITS VS 1
  - INTEGRATION OF 4 UNITS VS 2

OTV-1233
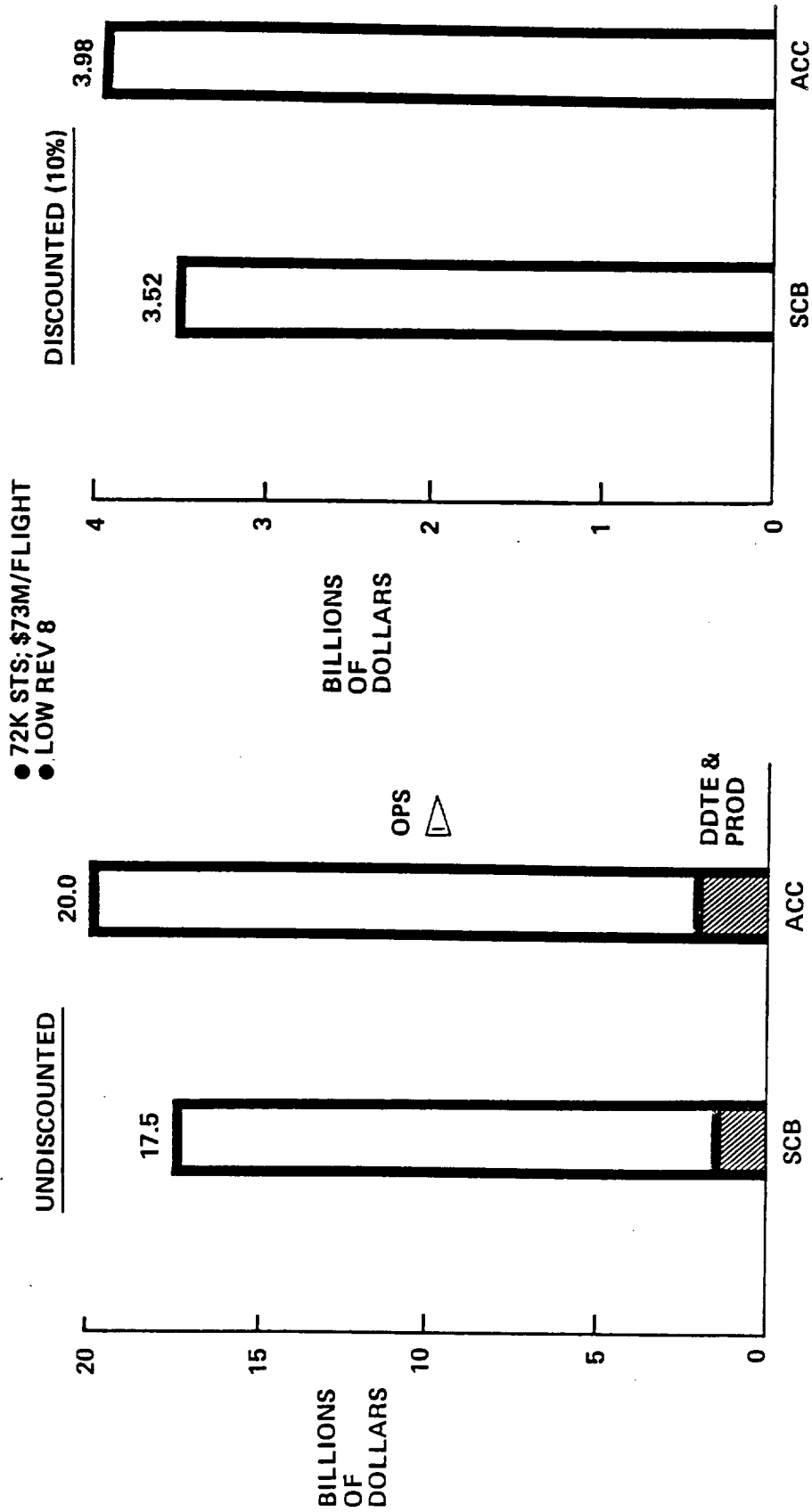
Figure 5.3.2 Ground Based Delivery Mode Trade OTV Program LCC Comparison

OTV-1218

OTV-1191

Table 5.3-4 GB OTV Delivery Mode LCC Breakdown

● 72K STS

OTV DELIVERY MODE

	SCB	ACC-107	ACC DIFFERENCE
DDTE			
OTV	(1317)	(1458)	
AUX. PROP TANK	999	968 √	LESS PROP, 42K VS 47K
LWACC	107	107	—
STATION ACCOM	—	172	REQUIRED FOR LAUNCH
TECHNOLOGY	56	56	—
	155	155	—
PRODUCTION			
OTV	(223)	(572)	
AUX. PROP TANKS	177	186 √	RECOVERY NOT POSSIBLE
LWACC	26	357 √	STS SCAR
STATION ACCOM	—	9	—
	20	20	
OPERATIONS			
LAUNCH	(15944)	(17997)	
	15002	16163	MORE MULTIMANIFEST FLIGHTS
ACC	—	320	EXPENDABLE EACH FLT.
BASIC OPS	789	848	—
Δ ON ORBIT OPS	80	468 √	MORE ASSY;DISASSY MORE COMPLEX AND HEAVIER
AEROBRAKE	73	198	
TOTAL LCC	$17,484M	$20,027M	

√ ITEMS DIFF. FOR ACC-104; ITS LCC = $18,796M

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It should be noted however that another ACC OTV concept (No. 104) was analyzed in a preliminary manner and was found to reduce the LCC for the ACC concept, but is still $1.4 billion more than the SCB concept. The 104 concept employed a single large LH_2 tank and four small LO_2 tanks. Such a configuration reduced the disassembly time and took up less space in the cargo bay so that the auxiliary tanks could also be returned. This concept also had a 43 ft diameter brake limitation so should the proper brake be used the cost advantage for the SCB OTV would be greater than that indicated.

5.3.4 Recommended Delivery Mode

The recommended GB OTV delivery has the OTV placed in the SCB. The principal reasons for this recommendation are shown in table 5.3-5. Less dry weight (including ASE) required to perform a mission resulted in more OTV payload capability on a given STS flight. As such, fewer flights were required resulting in less launch cost. From an operations standpoint the SCB concept does not have nearly as much on-orbit assembly and no on-orbit disassembly. The above factors contributed to the 13% cost advantage for the SCB OTV. It should also be repeated that the ACC OTV concept was given a waiver in terms of providing the required brake diameter for 82 missions. Should the proper brake have been used, the ACC OTV LCC would have been significantly increased and the margin of the SCB OTV would have been even more than indicated. A final point deals with the impact of the STS performance capability being 65K lbm rather than the baseline of 72K-lbm. Designs analysis for each concept has indicated the SCB OTV payload capability would be reduced from 12K to 9K-lbm for a single STS launch. The ACC OTV payload however would reduce from 8.4 to 5.3K-lbm. The result would be even a greater percentage of double STS launches for the ACC OTV and thus even a larger cost penalty.

OTV-1236

Table 5.3-5 Recommendation Ground Based OTV Delivery Mode

- SCB VERSUS ACC ---72K STS

● SCB OTV WITH BALLUTE AEROASSIST

  - 25% MORE PAYLOAD CAPABILITY

  - FEWER OTV FLIGHTS (15), FEWER STS FLIGHTS (5)

  - LESS OPERATIONAL COMPLEXITY

  - LCC (UNDISCOUNTED) SAVINGS OF $2.5 BILLION (12.5%)

  - LCC (DISCOUNTED) SAVINGS OF 13%

  - SCB OTV COST MARGIN INCREASES OVER ACC OTV WHEN BOTH USE 65K STS DUE TO RESULTING PAYLOAD CAPABILITY

6.0 STATION OTV ACCOMMODATIONS AND PROPELLANT LOGISTICS

A major contributor to the outcome of the basing trade is the impact of the station accommodations, station close proximity operations, and propellant logistics necessary to support a space based OTV. Descriptions of these elements and trades are presented in Volume II, Book 4 and Volume IV. A summary of the top level trades and key features of these elements is presented in the following paragraphs.

6.1 TRADES

Trades associated with propellant logistics and station accommodations and close proximity operations are summarized in table 6.1-1. In the area of propellant logistics, highlighted in figure 6.1-1, we found that propellant delivery to the Station for a SB OTV was more cost effective if the Orbiter stopped at 150 nmi and the OMV was sent from the Station to the Orbiter to pick up the propellant supply tank, deliver it to the Station and return an empty tank to the orbiter. Replenishment of the supply once delivered to the Station indicated either fluid transfer or tank exchange is worth further consideration. The propellant logistics concept selected to complete our OTV program analysis was that of using a tanker (MLI wrapped) which transferred propellant to a permanent dewar storage tank at the Station. A propellant transfer time (between storage tanks and OTV) of 7 hours involving 5 hours for filling and 2 hours for chilldown was found to be most cost effective and required 20 kw of Station power. The relative large power requirement was necessary to compress the gases resulting from chilldown.

OTV accommodations trades included consideration of where the propellant tanks should be located and the means used to transfer the propellant. The options are illustrated in figure 6.1-2. Storage at the Station with tank propellant screen acquisition systems was judged to have the best overall characteristics. An additional benefit of this concept from a study standpoint was that storage at the Station could be adequately assessed before the Station design gets finalized. Hangars for the SB OTV's are necessary for debris/meteoroid protection when the OTV's are stored at the Station. In addition, the hangar if adequately sized could simplify maintenance on the OTV. Our analysis indicated hangar sizing for maintenance was more effective than a smaller hangar that required moving the OTV outside for maintenance. Concepts considered for the launch and retrieval of OTV are shown in figure 6.1-3. The most effective means for launching and retrieving the OTV relative to the Space Station was through incorporation of a cold gas N_2 system directly into the OTV. The cold gas system was

OTV-833

Table 6.1-1. Space Station OTV Accommodations and Propellant Logistics △1

TRADE AREA	OPTIONS	SELECTION	RATIONALE
● PROPELLANT LOGISTICS			
● DELIVERY MODE	● ORBITER ONLY		
	● ORBITER + OMV ————	✳	● LOWER COST PER POUND ($1235 VERSUS $1362)
● REPLENISHMENT MODE	● FLUID TRANSFER ———— (TANKER + STORAGE TANK)	✳	● SLIGHTLY LOWER LCC— BOTH CONCEPTS VIABLE
	● TANK EXCHANGE		
● TRANSFER TIME STORAGE TANK TO OTV	● 7 TO 10 HRS	7 HRS	● LEAST POWER AND COST
● ACCOMMODATIONS			
● PROPELLANT STORAGE FACILITY	● INTEGRAL WITH STATION—	✳	● LEAST COST AND OPERATIONAL ISSUES
	● TETHERED TO STATION		
	● FREE FLYING PLATFORM		
● SERVICING LOCATION	● INSIDE HANGAR ————	✳	● LOWER COST AND IMPROVED OPERATIONS
	● OUTSIDE HANGAR		
● LAUNCH AND RETRIEVAL	● ONBOARD SYSTEMS————	✳	● LEAST COST AND SIMPLIFIED PROXIMITY OPERATIONS
	● USE OMV–BOTH LEGS		

△1 SEE JULY 16 REPORT

DELIVERY MODE

- OPTIONS

- ORBITER DIRECT INSERTION

- ORBITER AND OMV (√)
  (LEAST COST PER POUND)

- ANNUAL REQUIREMENT (TYP 2001) = 550,000 LBS
- SCAVENGE SUPPLY PER YEAR = 180,000 LBS (CARGO BAY)
- REMAINING PROP BY TANKER

SUPPLY MODE

- OPTIONS

- TANK EXCHANGE

- TANKER WITH STORAGE TANKS (√)
  (LOWEST LCC)

- LH$_2$ TANK
- ISOGRID TANKS
- MLI WRAPPED
- SCREEN ACQUISITION
- DRY WEIGHT = 6480 LB
- LO$_2$ CAPACITY = 53150 LB
- LH$_2$ CAPACITY = 8860 LB

LO$_2$ TANK

HELIUM STORAGE
FOR ABORT DUMP

14.3 FT

31.3 FT.

270 NMI

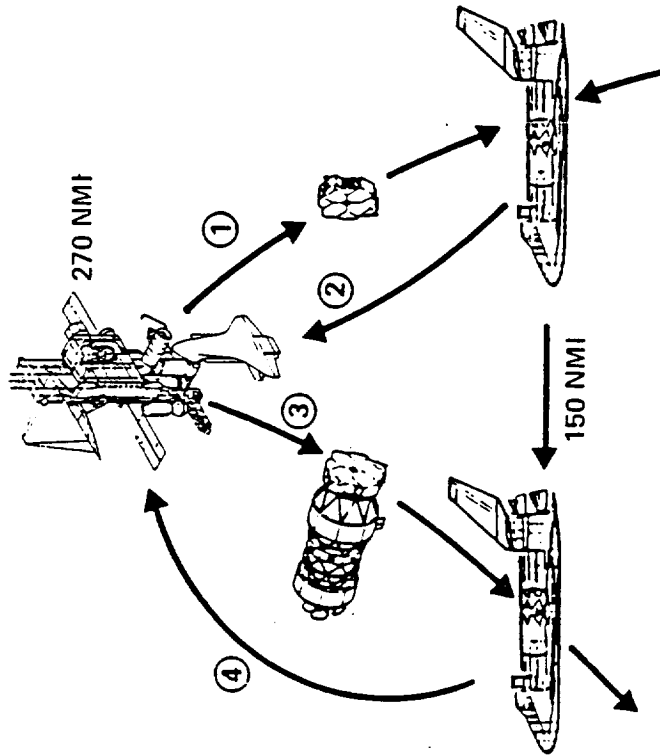150 NMI

① ② ③ ④

OTV-873
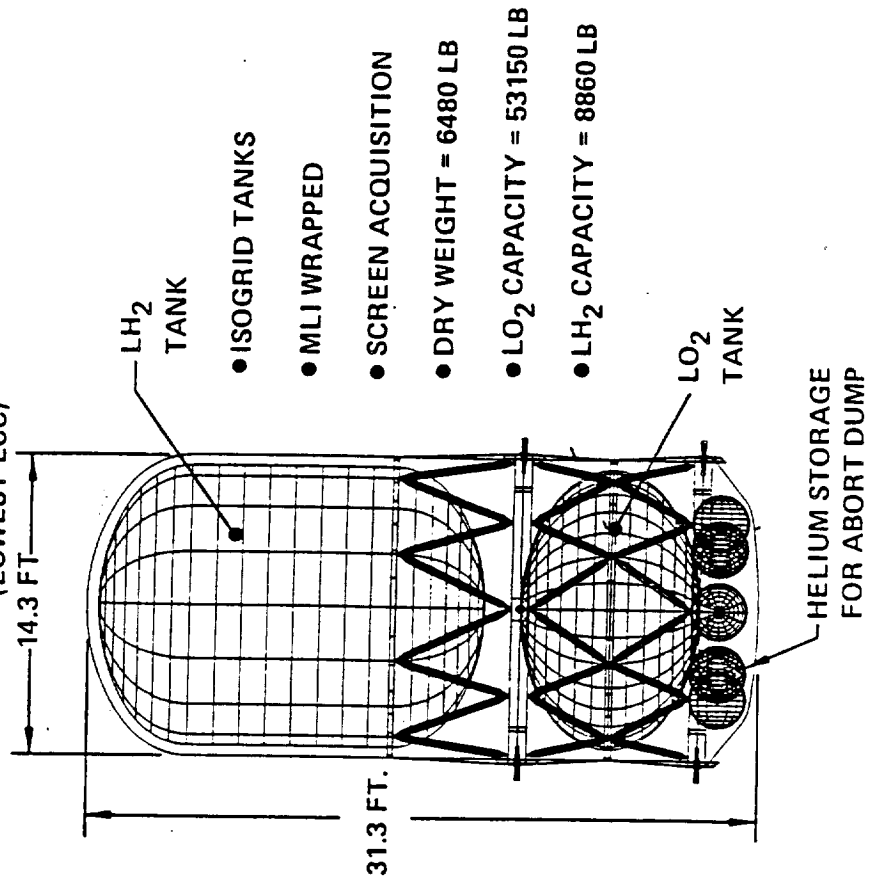
Figure 6.1-1 Propellant Delivery and Supply

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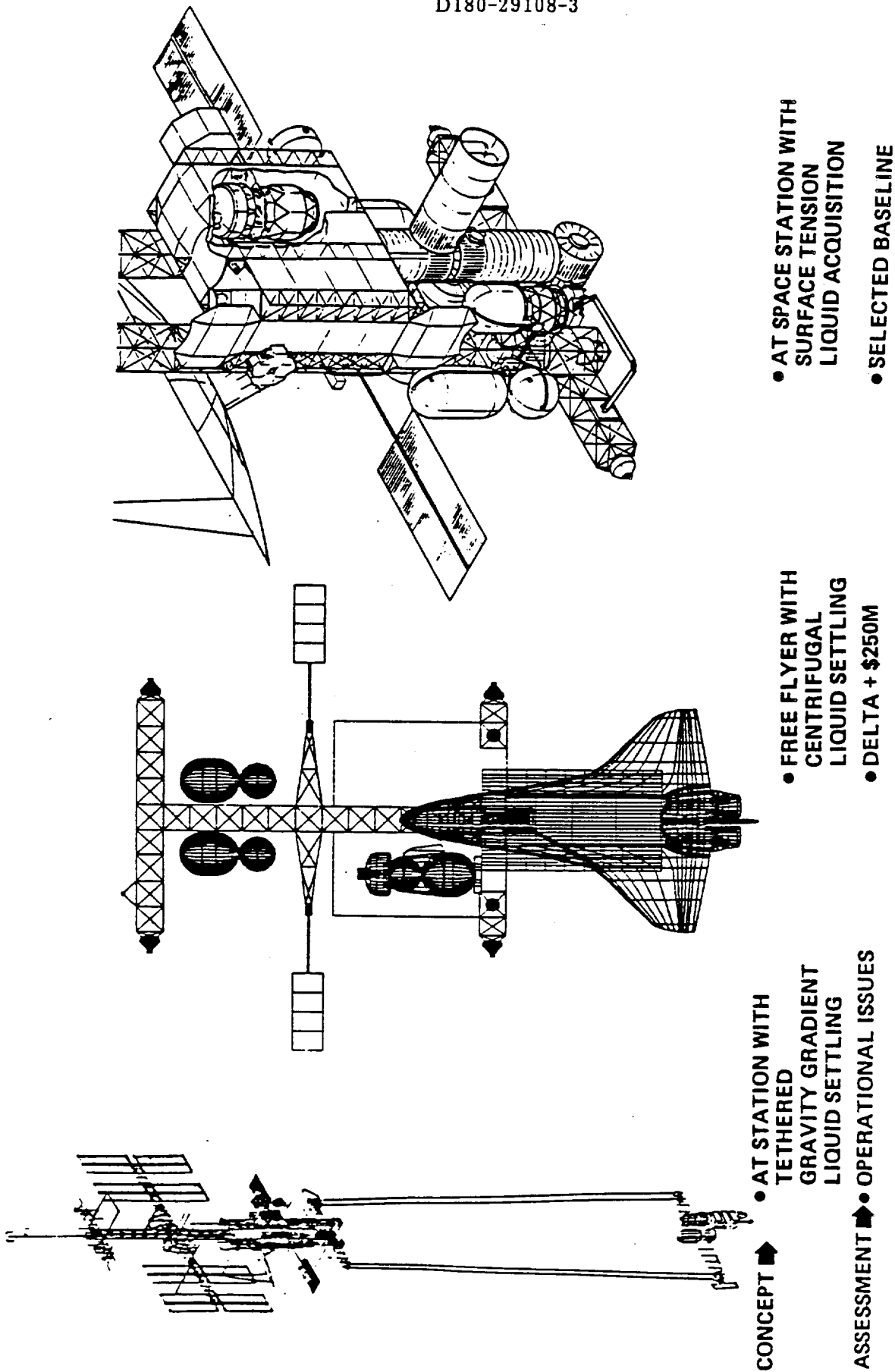
Figure 6.1-2 Propellant Storage Location Trades

CONCEPT

- AT STATION WITH TETHERED GRAVITY GRADIENT LIQUID SETTLING

- AT STATION WITH FREE FLYER WITH CENTRIFUGAL LIQUID SETTLING

- AT SPACE STATION WITH SURFACE TENSION LIQUID ACQUISITION

ASSESSMENT

- OPERATIONAL ISSUES

- DELTA + $250M

- SELECTED BASELINE

OTV-813

OTV AUTONOMOUS DEPLOYMENT

- COST/FLIGHT = $2.4 M
- DDTE = $0.7 M

OTV DEPLOYMENT WITH OMV

- COST/FLIGHT = $4.0 M
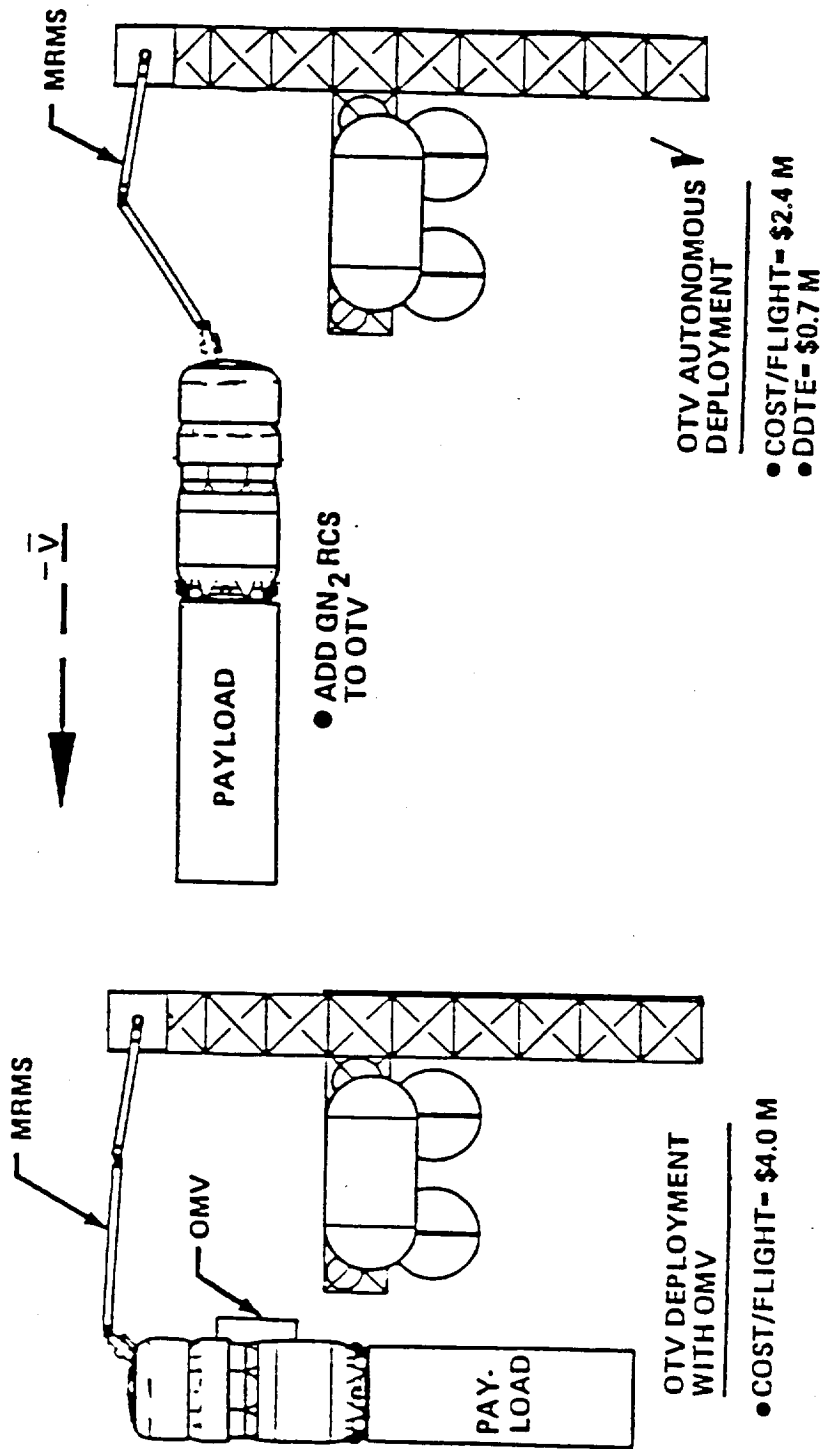
$\sqrt{}$ SELECTED

- INITIAL POSITIONING WITH MRMS AFTER PAYLOAD MATING AND CHECKOUT

- DEPARTURE IN $-\bar{V}$ DIRECTION

- RETRIEVAL ACQUISITION EFFECTED BY MRMS

Figure 6.1-3 OTV Deployment

OTV-1208

essentially the same as that used by the OMV. The selected approach eliminated two separate OMV flights to accomplish the OTV launch and retrieval.

6.2 BASELINE SYSTEMS

The baseline propellant logistics system is shown in figure 6.2-1. A typical annual propellant delivery requirement for a SB OTV after the year 2000 is over 550,000 lbs. A portion of this can be provided by the scavenge propellant concept which involves a combination of ground loading and transfer of excess propellant from the shuttle's external tank (resulting from volume limited launches) into scavenge tanks for subsequent delivery to the Station storage tanks. We have assumed the ACC method of scavenge which provides 200,000 lbs of the annual requirement. The remaining propellant therefore must be delivered using a tanker. Characteristics of the tanker are indicated. The tanker was a MLI wrapped design with screen acquisition and allows 60,000 lbs to be transferred into the orbital storage tanks.

Characteristics of the baseline propellant storage system at the Station are also indicated. A total capacity of 186,000 lbs has been provided resulting from the assumption of having enough propellant to perform a rescue mission of a manned flight to GEO and accommodating two scavenge deliveries at maximum loadings. The resulting system consists of two hydrogen and two oxygen tanks. Both use vapor cooled shields and MLI to minimize on-orbit boiloff and screen acquisition systems for capturing the propellant under near zero g conditions. A gas storage system is also required due to the "no vent" rule imposed by the Station. This gas occurs as a result of boiloff and vaporization as the transfer lines and OTV are chilled during the propellant transfer operations. This gas could be used to provide a steady state power level of 3.5 kW and 84 lbs of water per day.

The selected location for the SB OTV accommodations at the Space Station is shown in figure 6.2-2. The indicated location is adjacent to the crew modules and is the result of a number of considerations including constraints imposed by the Station such as view factors for experiments, power generation systems, radiators, crew visibility, exclusion from zones associated with Station RCS plumes or orbiter docking. Finally, there was the implications on overall Station c.g., movement of the OTV and its payloads around the Station and ease of accessibility of the crew to the hangars. Hardware elements added to the Space Station to support OTV operations are the propellant storage tanks, the propellant transfer system, and the OTV servicing hangar.

ORBITAL PROPELLANT STORAGE

LH₂ SYSTEM

14.3 FT

28.9 FT

- 2 TANKS/DEWAR
- SCREEN ACQUISITION
- CAPACITY = 13,286 LBS (EA.)
- DRY = 5686 LBS (EA.)

LO₂ SYSTEM

14.3 FT. DIA.

- 2 TANKS/DEWAR
- SCREEN ACQUISITION
- CAPACITY = 79714 LBS (EA)
- DRY = 2063 LBS (EA)

NO VENT STORAGE SYSTEM

- STORE AT 2000 PSIA
- GENERATE 3.5 KW (STEADY) AND 84 LBS WATER/DAY
- PROVIDE TANK PRESSURIZATION

STS PROPELLANT TANKER

14.3 FT

31.3 FT.

LH₂ TANK

- ISOGRID TANKS
- MLI WRAPPED
- SCREEN ACQUISITION
- DRY WEIGHT = 6400
- LO₂ CAPACITY = 53150
- LH₂ CAPACITY = 8060

LO₂ TANK

HELIUM STORAGE FOR ABORT DUMP

Figure 6.2-1 Propellant Logistics System

OTV-1781

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OTV-829
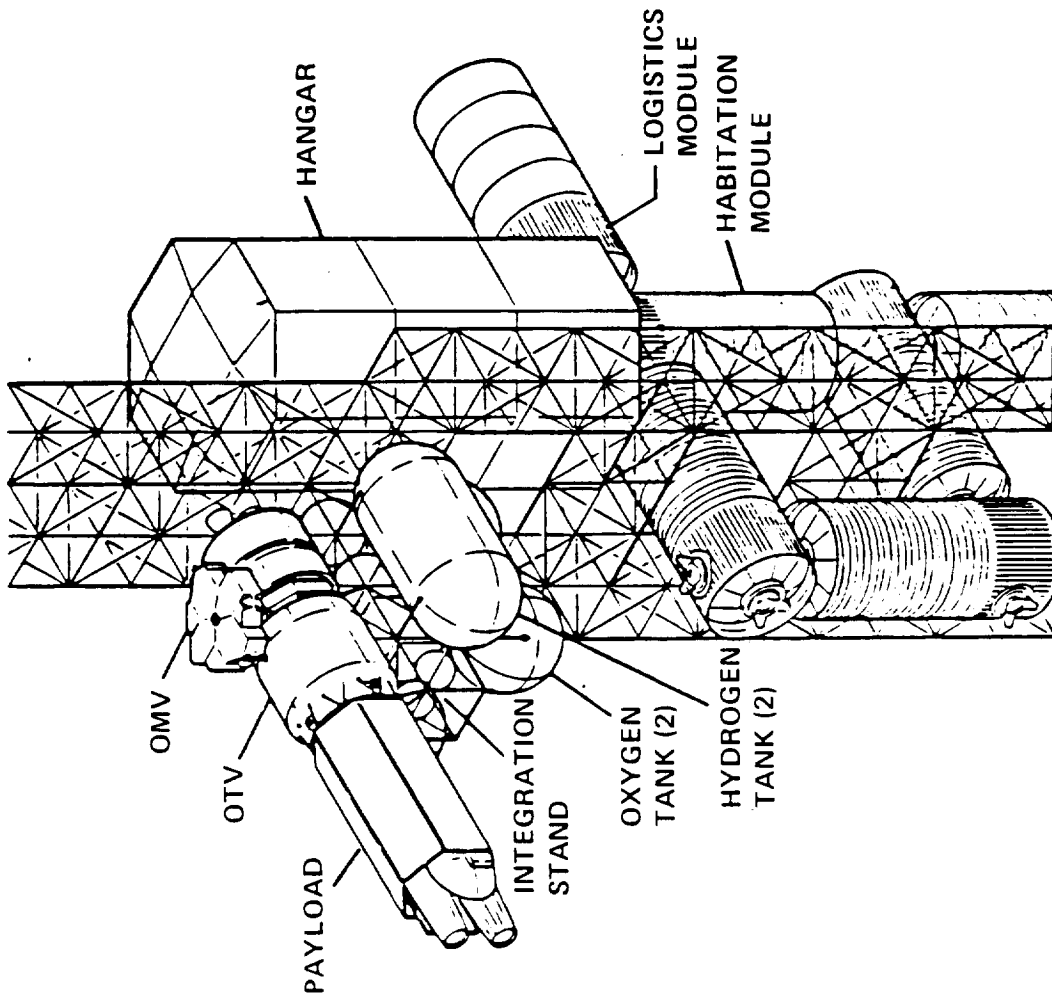
FEATURES

1. GOOD COMPROMISE OF STATION C.G. CONSIDERATIONS, MOVEMENT AROUND STATION AND ACCESSIBILITY

2. HANGAR ADJACENT TO COMMON MODULE FOR DIRECT ACCESS

3. PROPELLANT STORAGE NEAR STATION VERTICAL C.G. AND BALANCES LOGISTICS MODULE OFFSET

4. INTEGRATION STAND NEAR C.G., PROPELLANT STORAGE AND HANGAR

HANGAR

LOGISTICS MODULE

HABITATION MODULE

OMV

OTV

INTEGRATION STAND

OXYGEN TANK (2)

HYDROGEN TANK (2)

PAYLOAD

Figure 6.2.2. Station SB OTV Accomodations

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Accommodations for a GB OTV are limited to a small hangar to store an auxiliary propellant tank and an integration area for when the main stage and auxiliary tank/payload require physical integration.

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7.0 OTV BASING/PROGRAM EVOLUTION TRADE

The most significant issue influencing the overall OTV program is that of whether the OTV should be ground based, space based or use both in a combination mode. This trade was performed several times during the course of Phase I. Each of these iterations reflected updates in study groundrules and further understanding of the concepts and basing options. Only the results of the final iteration will be presented in this report as it supercedes all prior work.

In addition to the key groundrules specified in section 2.0, the following groundrules are significant to this trade.

1. Use the total Rev 8 low mission model.

2. All reusable configuration options use advanced cryogenic engines, ballute aeroassist, and cost optimum and man-rating scar redundancy for unmanned flights.

3. The reference program option consists of existing expendable upper stages.

4. Reflects results of the KSC/Boeing OTV Operations Study (Jan. 1986).

5. Reflects results of MSFC/Martin Marietta Aerospace Propellant Scavenging Study (as of Jan. 1986)---200K-lbm per year.

6. STS launch cost based on Shuttle Users Charge Policy. (Full charge occurs once three quarters of weight or length capacity is reached but does not exceed a 1.0 factor for more demand payloads.)

7. Each OTV payload, tanker, OTV main stage, OTV plus payload, or auxiliary propellant tank plus payload is treated as an individual cargo element for purposes of establishing STS users charge. ASE length or weight is also included.

8. Crew (per person) cost per hour at the Space Station were $17,000 for IVA and $75,000 for EVA.

9. The baseline performance capability of the STS is 72K lbm to 140 nmi/28.5 degree.

7.1 BASELINE COMPARISON

This section compares several candidate basing options that use the baseline groundrules specified in the preceding paragraph.

7.1.1 Basing Options

Three basic options in addition to a reference option were analyzed. The characteristics of each option in terms of development and operational schedule,

mission application and vehicle characteristics are presented in the following paragraphs.

The reference option in this trade involved continued use of existing upper stages including PAM-D and D-II, IUS, and Centaur. The utilization of these stages in performing the mission model and their key characteristics are indicated in figure 7.1-1. These stages do not have any development cost and require a total of 206 flights to perform the 145 flight OTV mission model. The difference in flights is attributed to multimanifesting by the OTV and for large missions the need to have a transportation system composed of two Centaurs. Stage cost characteristics were provided by NASA.

Option 2 shown in figure 7.1-2 relates to the previously selected reusable GB OTV concept. This approach has the GB OTV main stage beginning flights in 1994 and does not require the auxiliary tank and Station accommodations until the 20,000 lbs delivery missions beginning in 2001. A Station interface also occurs on missions involving payloads ≥ 30 ft. The stage and payload are delivered to the Station on separate STS flights and are then attached to each other. The main stage is used on all flights and the auxiliary tank on 36 flights. Weights for the "main stage only" reflect an unmanned cost optimum redundancy configuration whereas the main plus auxiliary tank values are for manned GEO missions. The configuration and weight summary for a manned sortie mission is shown in figure 7.1-3. This configuration is the same as previously discussed in Section 5.3 with the exception of the auxiliary tank which has been changed to a two-tank rather than four-tank arrangement resulting in improved performance.

Option 3, presented in figure 7.1-4, is primarily the SB OTV concept; however, by study groundrules this concept cannot begin until 1997 when the growth or FOC space station was to be available. Consequently, this option uses existing upper stages for the first three years of the mission model. Station accommodations must also be ready at the same time as the SB OTV. The SB OTV performs 124 of the 145 flights in the model. The baseline SB ballute brake OTV configuration and key features as sized by the manned mission is shown in figure 7.1-5. A major factor associated with any option using a SB OTV is the crew hours associated with preparation of the vehicle for the next flight. A summary of the required hours to perform this operation as indicated by the Boeing OTV Operations Study for KSC is presented in figure 7.1-6. Also indicated are the values developed by the Boeing OTV Concept Definition team earlier in the study. The Operations Study values are higher and are generally attributed to a more in-depth analysis. Based on the crew cost specified in the groundrules, the processing cost for each SB OTV flight is $9 million.
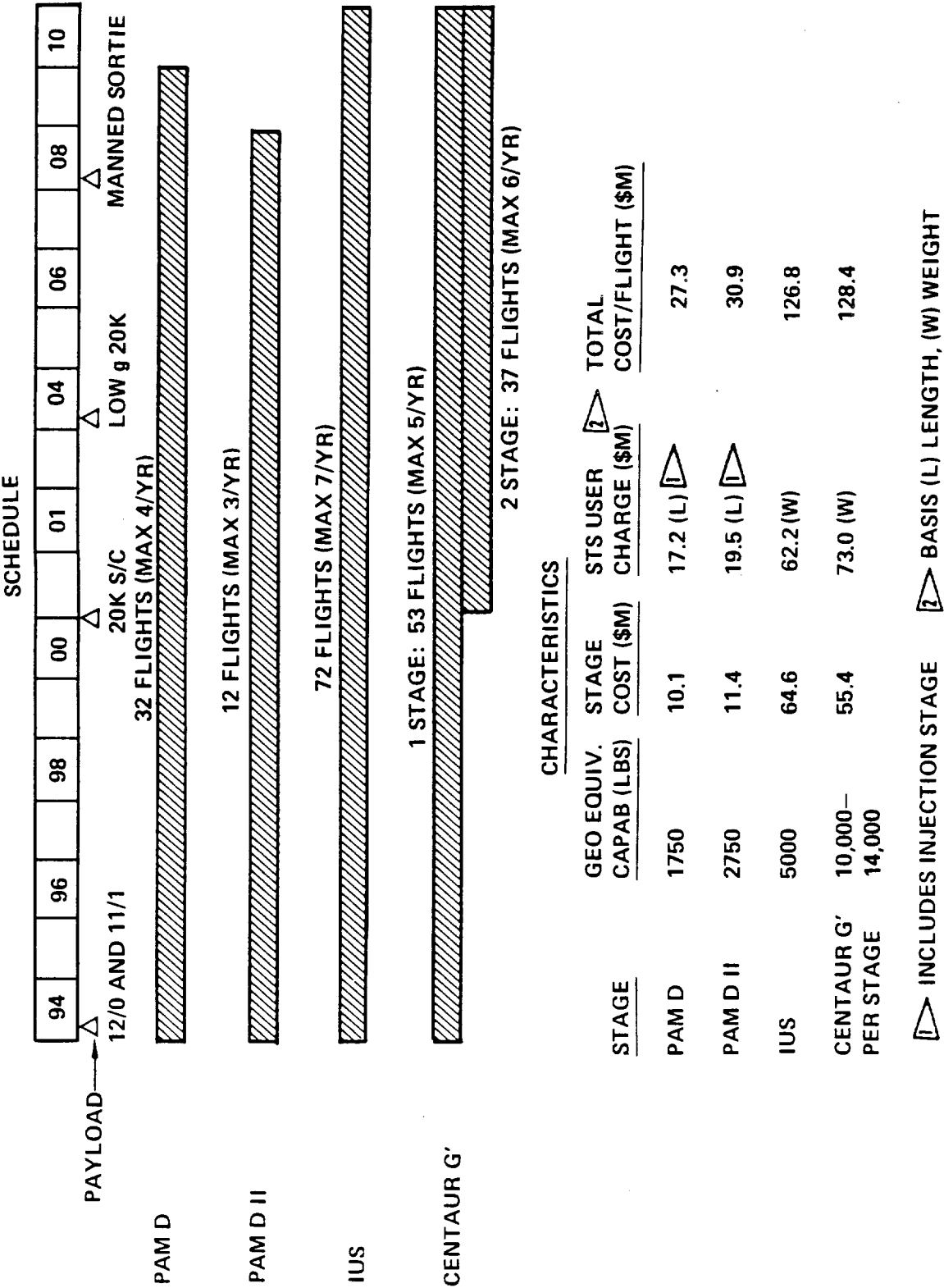
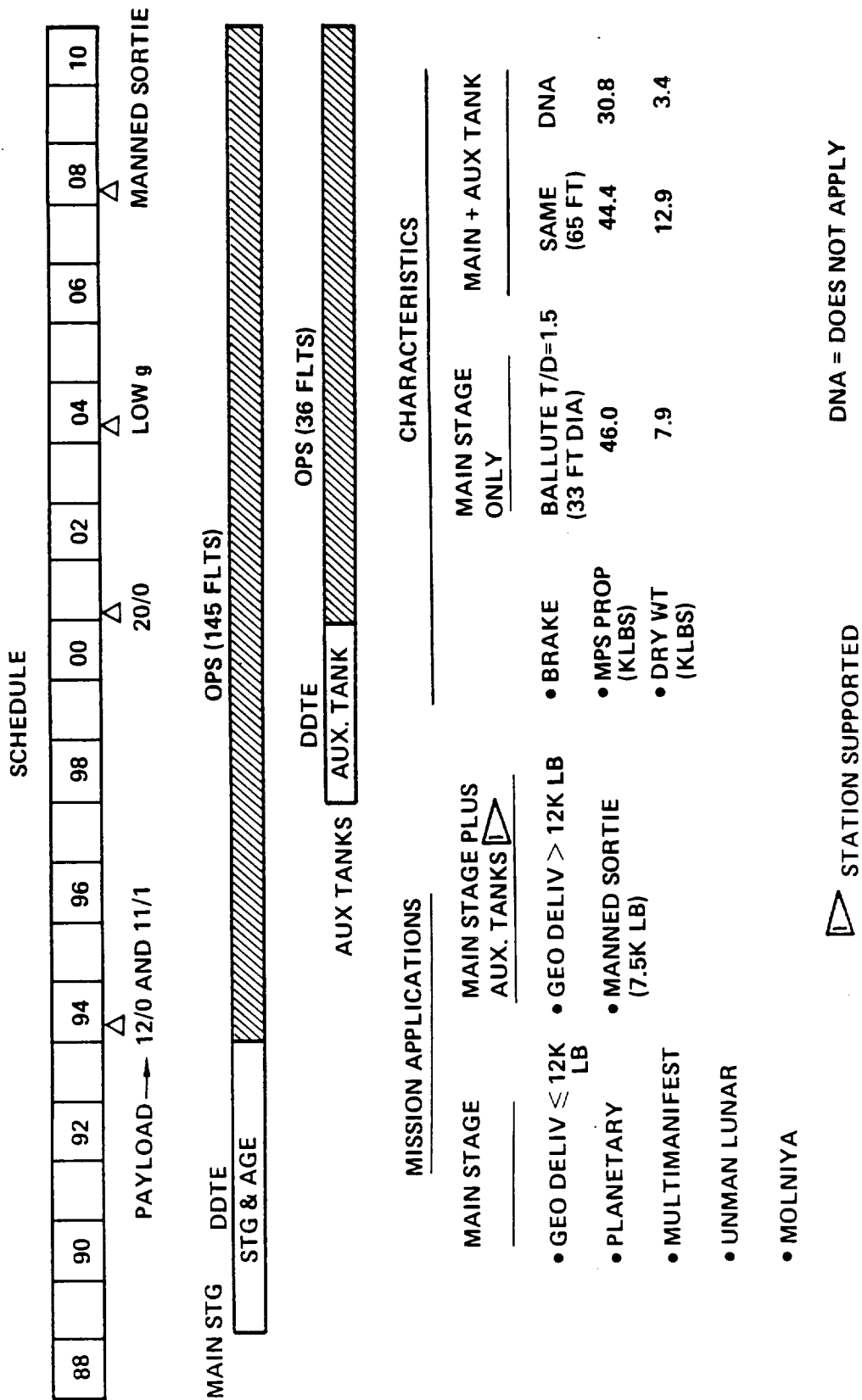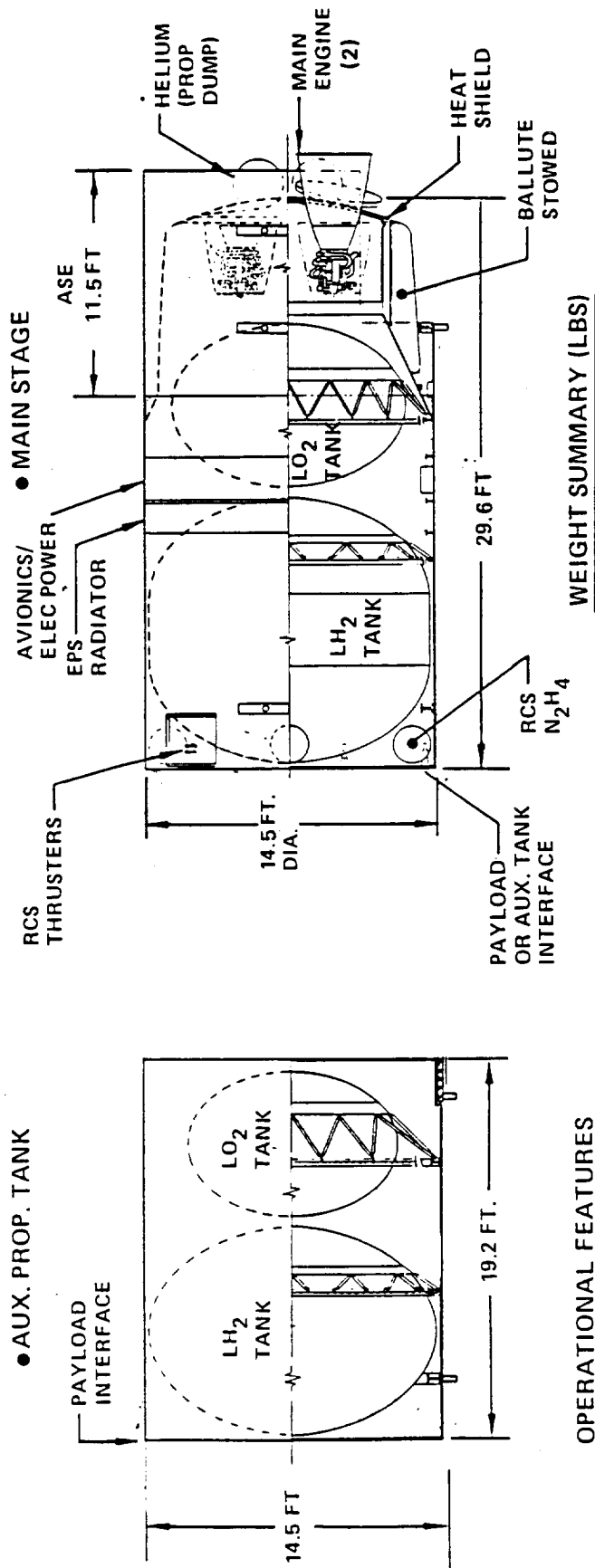Figure 7.1-1. Expendable Upper Stage Fleet, Option 1 (Reference)

SCHEDULE

94	96	98	00	01	04	06	08	10

PAYLOAD △ 12/0 AND 11/1 △ 20K S/C △ LOW g 20K △ MANNED SORTIE

PAM D — 32 FLIGHTS (MAX 4/YR)

PAM D II — 12 FLIGHTS (MAX 3/YR)

IUS — 72 FLIGHTS (MAX 7/YR)

CENTAUR G' — 1 STAGE: 53 FLIGHTS (MAX 5/YR) — 2 STAGE: 37 FLIGHTS (MAX 6/YR)

CHARACTERISTICS

STAGE	GEO EQUIV. CAPAB (LBS)	STAGE COST ($M)	STS USER ⟨2⟩ CHARGE ($M)	TOTAL ⟨2⟩ COST/FLIGHT ($M)
PAM D	1750	10.1	17.2 (L) ⟨1⟩	27.3
PAM D II	2750	11.4	19.5 (L) ⟨1⟩	30.9
IUS	5000	64.6	62.2 (W)	126.8
CENTAUR G' PER STAGE	10,000—14,000	55.4	73.0 (W)	128.4

⟨1⟩ INCLUDES INJECTION STAGE   ⟨2⟩ BASIS (L) LENGTH, (W) WEIGHT

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SCHEDULE

88	90	92	94	96	98	00	02	04	06	08	10

PAYLOAD → 12/0 AND 11/1   20/0   LOW g   MANNED SORTIE

MAIN STG   DDTE

STG & AGE

OPS (145 FLTS)

DDTE   OPS (36 FLTS)

AUX. TANK

AUX TANKS

MISSION APPLICATIONS

MAIN STAGE	MAIN STAGE PLUS AUX. TANKS △
• GEO DELIV ≤ 12K LB	• GEO DELIV > 12K LB
• PLANETARY	• MANNED SORTIE (7.5K LB)
• MULTIMANIFEST	
• UNMAN LUNAR	
• MOLNIYA	

CHARACTERISTICS

	MAIN STAGE ONLY	MAIN + AUX TANK	
• BRAKE	BALLUTE T/D=1.5 (33 FT DIA)	SAME (65 FT)	DNA
• MPS PROP (KLBS)	46.0	44.4	30.8
• DRY WT (KLBS)	7.9	12.9	3.4

△ STATION SUPPORTED   DNA = DOES NOT APPLY

Figure 7.1-2. Reusable Ground Based OTV, Option 2

Figure 7.1-3 Selected Concept GB Ballute Braked OTV

OTV-929

WEIGHT SUMMARY (LBS)

	10K △1 MAIN STG	MANNED SORTIE MAIN	AUX.
●DRY	7961	9920	2990
●MAIN PROP.	46790	46790	31238
●OTHER FLUID	758	1655	
●STG STARBURN	55509	58365	34228
●PAYLOAD (NET)	10000	----	7500
●RACK	1000	----	
●ASE	6390	6390	4601
●LIFTOFF	72899	64755	46329

△1 MULTIPAYLOAD FLIGHT PROP LOAD CAN DELIVER 12K LB

OPERATIONAL FEATURES

● STARTBURN AT 120 NMI
● MAIN STAGE ---- ALL FLIGHTS
● AUX. TANK ---- 36 FLIGHTS
  (PAYLOAD > 12K LB DELIV)
  (MANNED ROUND TRIP)
● MAIN STAGE + AUX TANK FLIGHTS
  ● AUX. TANK AND PAYLOAD TO STATION
  ● MAIN STAGE TO STATION
  ● MAIN/AUX/PAYLOAD INTEG. AT STATION

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Figure 7.1-4. Reusable Space Based and Reusable Space + Ground Based OTV, Options 3 and 4
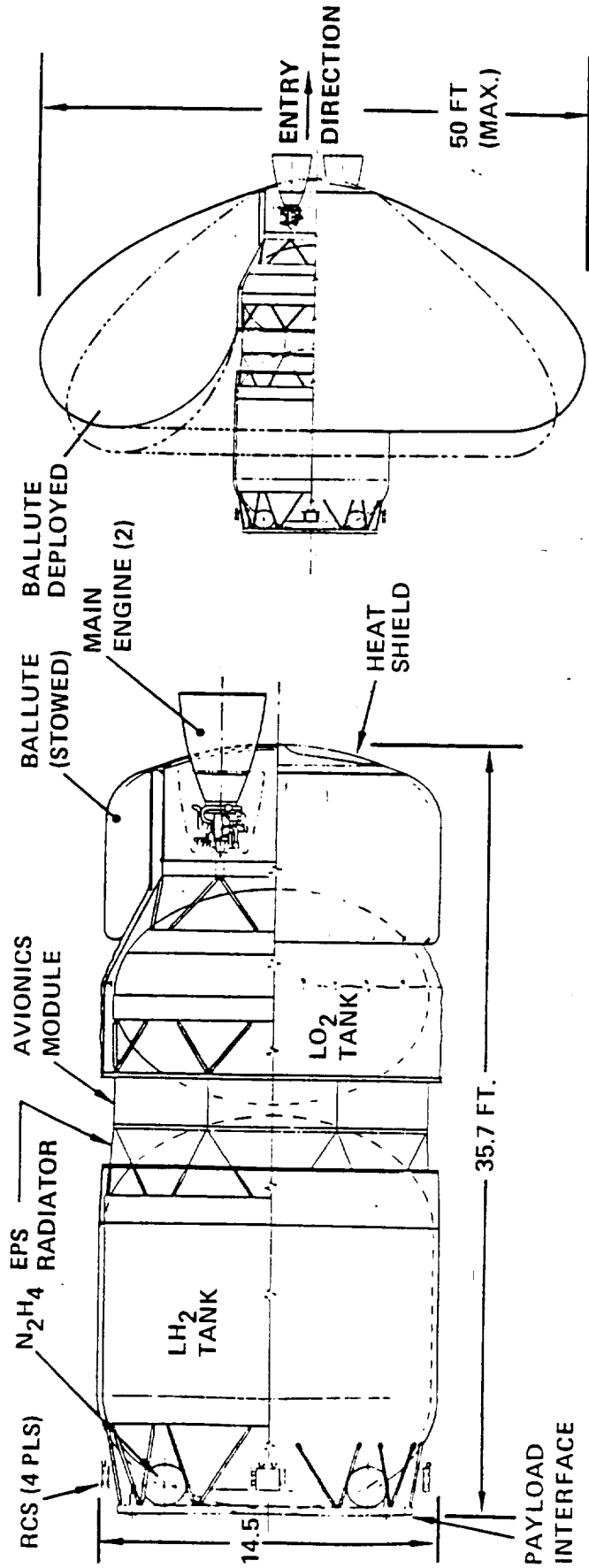
STAGE WEIGHT SUMMARY (LBS)

- DRY   9189
- MAIN PROP.   63,890   ⟨1⟩
- OTHER FLUIDS 1,061
- STARTBURN   74,140

⟨1⟩ FOR MANNED GEO SORTIE (7.5K LB R.T.)
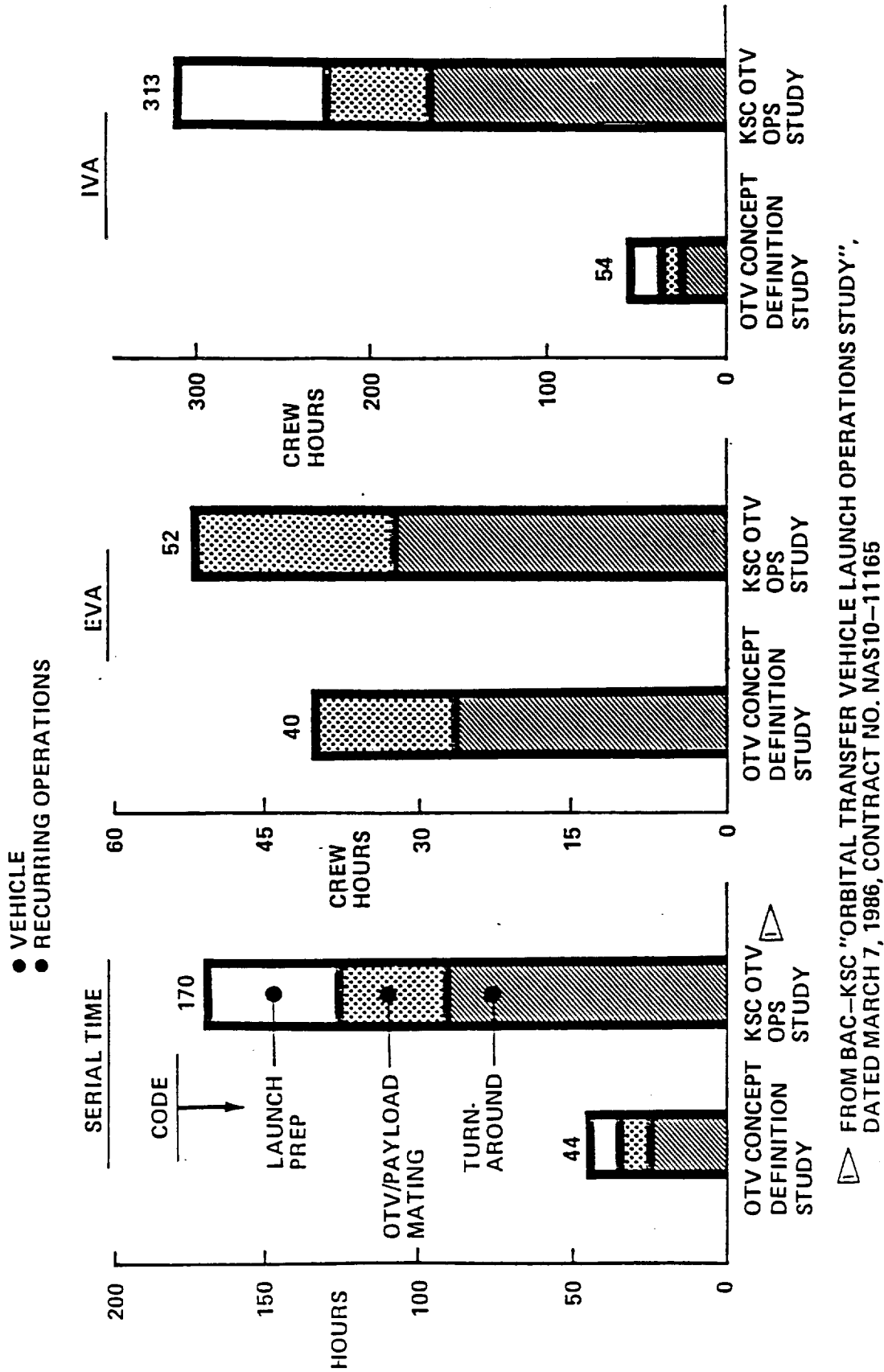OR 20K LB GEO DELIV

UNIQUE FEATURES

- BALLUTE
  - NEXTEL/CS 105
  - 1500°F BACKWALL
  - TURNDOWN RATIO = 1.5
  - 1 USE
- HEAT SHIELD—RSI
  - 20 USES
- NO INITIAL ON-ORBIT ASSEMBLY

Figure 7.1-5 SB Ballute Braked OTV

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Figure 7.1-6 SB OTV On-Orbit Processing

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The fourth option also shown in figure 7.1-4 involves use of both the ground and space based OTV's. The program begins with a GB OTV main stage which has sufficient capability to perform 81 out of 145 flights using a single STS launch. The remaining 64 flights can be done more effectively using the SB OTV beginning in 1997. A large degree of commonality exist between SB and GB OTV in the areas of main engine, RCS, avionics, and ballute design. A variation of this option was to have the GB OTV main stage operate only until the SB OTV was available. This variation was analyzed early in the study (midterm) and indicated that (1) it was more effective than use of existing upper stages for 3 years but (2) it was not as effective as continued use of the GB OTV throughout the mission model as defined in option 4.

7.1.2 Cost Comparison

The LCC comparison of the options is presented in figure 7.1-7. Use of existing upper stages to perform the low mission model tends to result in a significant penalty relative to any of the reusable OTV options. The least cost (undiscounted) approach is provided by option 4 which is the combination of reusable GB plus SB OTV's although the DDT&E and production is considerable higher than the all GB OTV concept. From a discounted standpoint (primary selection criteria), the all GB OTV option results in the least cost because its lower DDT&E cost offsets the lower operations cost of the GB plus SB OTV concept.

A more in depth breakdown of the major cost contributors in the basing trade is presented in table 7.1.-1. In the area of DDT&E, the options using SB OTVs are higher because of Station accommodations and tanker cost and the combination system has the additional cost due to developing both a GB and SB OTV. Production costs are higher for the options using space basing again because of the Station accommodations and tanker provisions. In the area of operations, the space based options require the greatest cost in the initial orbital placement of Station accommodations. Option 3 must rely on existing upper stage during the first three years of missions, and this contributes to it having a higher cost. Variation in operations costs for 1997-2010 are due to a variety of reasons. The all GB OTV costs are driven up considerable because 80 missions require two shuttle flights (each with average load factor of 0.75). Option 3, relying on SB OTV's, has slightly higher cost. Contributing to the SB OTV's operations costs relative to the GB OTV is the higher cost for OTV turnaround at the Station, launch of subsequent empty OTV's to maintain the fleet, launch of OTV spares and Station accommodation spares, launch of the second set of Station accommodations, and tanker turnaround and spares. Option 4, involving both GB and SB OTV's, has a significantly
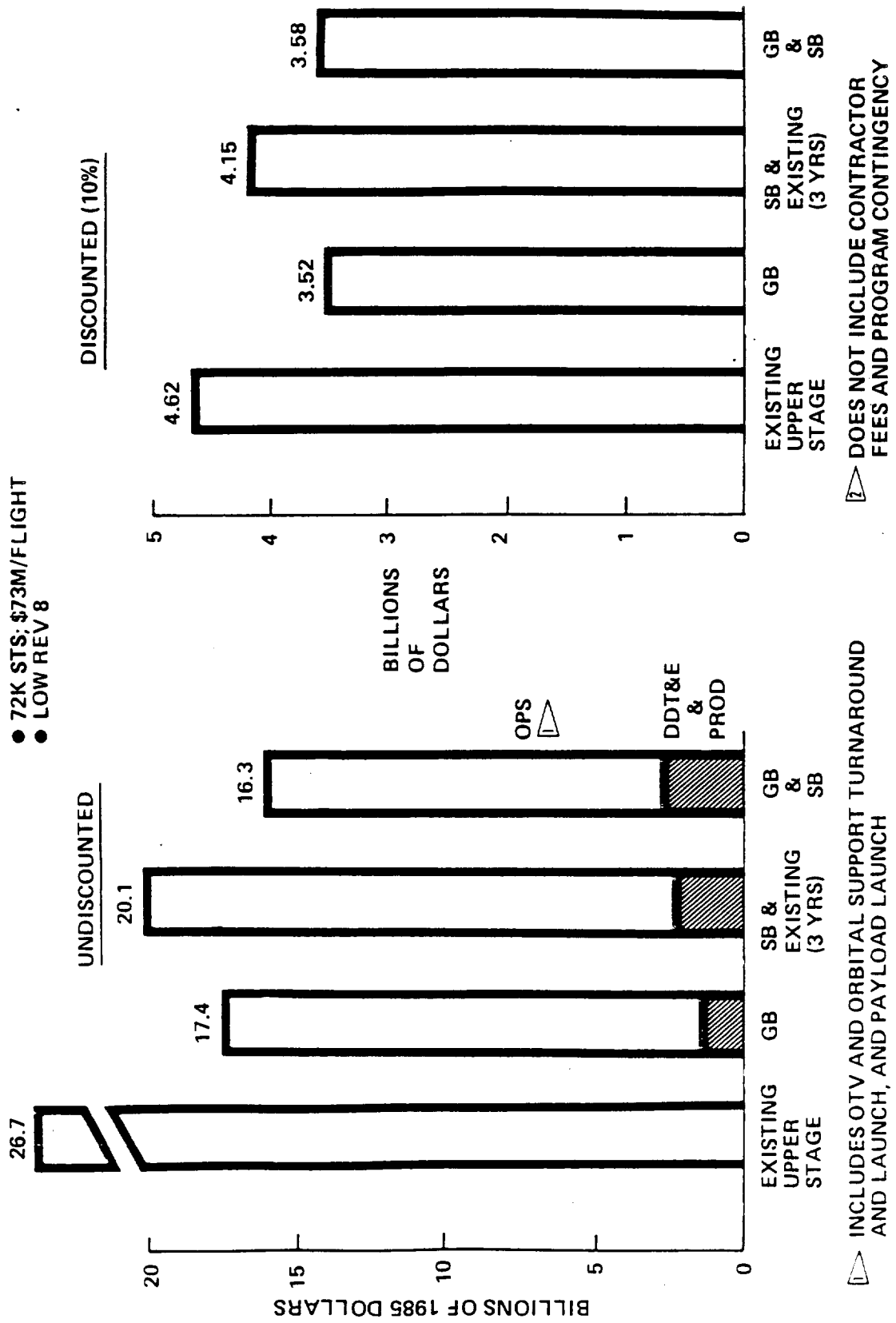
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Figure 7.1-7 OTV Basing Trade – Program LCC Comparison △2

Table 7.1.1 OTV Basing Trade – Program LCC Comparison

● LOW MODEL ● COST IN MILLIONS OF DOLLARS	OPTIONS FOR 72K STS			① EXISTING STAGES
	② RGB	③ RSB + EXPEND	④ RGB + RSB	
DDT&E	(1,317)	(2,058)	(2,434)	(0)
● OTV	1,106	1,059	1,435	
● STATION ACCOMM.	56	364	364	
● STS TANKER/SCAV . SYS	0	480	480	
● TECHNOLOGY	155	155	155	
PRODUCTION	(223)	(393)	(315)	(0)
● OTV	203	118	114	
● STATION ACCOMM.	20	123	71	
● STS TANKERS /SCAV. SYS	0	152	130	
OPERATIONS	(15,944)	(17,668)	(13,471)	(26,700)
● INITIAL PLACEMENT OF SB ELEMENTS	26	174	174	—
● 1994–1996 MISSIONS	1,990	2,773	1,990	2773
● 1997–2010 MISSIONS	13,928	14,721	11,307	23,927
UNDISCOUNTED	17,484	20,119	16,470	26,700
DISCOUNTED (10%)	3.52	4.15	3.58	4.62

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lower cost for this time period because it takes advantage of the best features of each type of OTV. The GB is very effective for GEO payloads $\leq$12K lbm and Molnyia deliveries. The Molnyia mission is done much more efficiently using GB rather than SB because the Shuttle can launch into a 57 degree inclination and thus the OTV only requires a 7 degree plane change instead of nearly 35 degrees if it were space based. The remaining missions are done more effectively using the SB OTV because the majority of its propellant can be obtained via propellant scavenging STS flights.

Further resolution on the operations cost is presented in table 7.1-2. In this case, emphasis is placed on cost associated with functional elements of the operations cost. The most significant contribution comes from launch cost which has been broken down by cargo type. The existing stages and payloads category for the 3 main basing options only applies to the SB OTV mode for the first three years. The difference in GB OTV + payload launch cost is due to fewer GB OTV flights for the GB + SB option. Payload only launch cost is less for the combination OTV option because it has fewer SB OTV flights. Propellant launch cost is also less for the combination option because most of its propellant is obtained via scavenging ($250/lbm) rather than via tanker ($1500/lbm). On-orbit processing cost is highest for the SB option because 121 flights are involved as opposed to only 64 SB OTV flights in the combination model. The GB OTV option value reflects 80 flights requiring only on-orbit mating of the main stage with payload or auxiliary tank/payload combinations rather than full servicing as required by space based OTV's.

Average cost per flight breakdown for GB and SB OTVs is shown in table 7.1-3. For the GB OTV there are 109 flights which cost $79 million each as compared with the average cost for a SB OTV of $119 million. However, for the remaining 36 flights of the mission model, the GB OTV concept requires launching the auxiliary propellant tank with payload on a separate flight from the main stage resulting in a cost per OTV flight of $153.7 million versus the SB OTV cost average of $119 million.

7.2 SENSITIVITIES

In addition to the baseline comparison of the basing options several sensitivities were investigated. These included the impact of an STS having 65K lbm capability, variation in the amount of scavenging propellant, and variation in the number of OTV flights. Sensitivity to use of a large unmanned cargo launch vehicle was analyzed during the last quarter of the study and reported in Volume IX.

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Table 7.1-2 Operations Cost Breakdown Basing Trade --- 72K STS

	GB OTV	SB OTV + EXISTING	GB OTV + SB OTV
LAUNCH	(14,982)	(15,474)	(11,873)
● EXISTING STAGES + PAYLOADS	—	2,773	—
● GB OTV + PAYLOAD	14,956	—	6,150
● PAYLOAD ONLY	—	5,828	3,008
● PROPELLANT	—	6,228	2,300
● SB OTV'S + SPARES	—	471	241
● STATION ACCOMMODATIONS	26	174	174
ON ORBIT VEHICLE PROCESSING	(80)	(1,143)	(606)
OTHER RECURRING COST △₁	(882)	(1,051)	(992)
TOTAL	15,944	17,668	13,471

△₁
- ● GROUND PROCESSING (OTV, TANKER)
- ● STATION ACCOMMODATIONS
- ● REFURB HARDWARE
- ● OMV ORBITAL SUPPORT
- ● MISSION CONTROL
- ● REFLIGHT

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Table 7.1-3 OTV Average Cost Per Flight

ITEM	GROUND BASED OTV		SPACE BASED OTV ONLY △
	MAIN STAGE	MAIN + AUX TANK	
TURNAROUND AND P/L MATING	1.5	1.6	9.2
OTV REFURB HARDWARE	1.5	1.5	1.5
OTV REFURB HARDWARE LAUNCH	---	---	2.8
REPLACEMENT OTV LAUNCH	---	---	1.0
P/L LAUNCH & INTEGRATION	1.5	1.5	48.5
OTV/PAYLOAD/AUX TANK LAUNCH	73.0	135.0	---
GROUND OPERATIONS	0.5	0.6	0.5
TANKER REFURB. HARDWARE	---	---	0.6
PROP. LAUNCH COST	---	---	49.2
TANKER TURNAROUND	---	---	0.2
ACCOMMODATIONS REFURB.	---	0.2	2.2
REFLIGHT COST	1.0	1.0	1.3
RELAUNCH ASE	---	0.4	---
OMV SUPPORT	---	.9	1.3
TOTAL (MILLIONS)	79.0	142.7	118.3
APPLICABLE FLIGHTS	109	36	124

△ THE OTHER 21 MISSIONS DONE USING EXISTING EXPENDABLES

7.2.1 65K STS Impact

Each of the basic options previously discussed in section 7.1.1 were evaluated for their impact should the performance capability of the STS be 65 K-lbm rather than 72K-lbm. No other groundrule involving cost was changed. In summary, each of the options required additional flights as indicated by table 7.2-1. Also included is the delta cost to the baseline that used a 72K-lb STS.

In the case of the GB OTV, 13 additional multiple manifest OTV flights were required and two 12K-lb payloads had to go to dual STS launches. The OTV configuration for the 65K-lb STS is shown in figure 7.2-1. The single launch payload capability for this OTV is 9K-lbm to GEO which brings about the extra launches. A small auxiliary tank (W_p = 13K-lbm) and large auxiliary tank (W_p = 39.6K-lbm) are used with the main stage configuration for 12K-lbm and 20K-lbm or 7.5K-lb round trip missions, respectively. A weight summary for this option is shown in table 7.2-2.

The SB OTV option does not require a change in OTV configuration because it is fueled on-orbit. The propellant delivery tanker however must be reduced in capacity from 61K-lbm to 55K-lbm resulting in 8 additional STS launches.

The GB and SB OTV option has the same number of delta launches for the GB OTV portion as specified earlier for the GB OTV only option. There is less of an increase for the SB OTV portion because again, most of its propellant is obtained by scavenging.

The summary LCC comparison for this case is presented in figure 7.2-2. The GB and SB OTV combination still gives the least undiscounted cost while the GB OTV only option provides the lowest discounted cost. A cost comparison of the options as a function of STS capability is shown in figure 7.2-3 (undiscounted) and figure 7.2-4 (discounted). It will be noted from these plots that the SB OTV option improves on a relative basis to the other options as STS performance capability decreases. This situation occurs because propellant can be manifested into the STS more efficiently than can an OTV with its payload. Projection from the discounted cost curve indicates however that the SB OTV option would not equal the cost of the other options until STS capability is reduced to approximately 50K lbm.

7.2.2 Propellant Scavenging

Propellant scavenging deals with the concept of transporting a limited amount of propellant to orbit for SB OTV use on shuttle flights that are volume rather than weight limited. A portion of the propellant can be loaded in the scavenging tanks on the ground and the remainder obtained from the propellant remaining in the external tank after the launch. This concept has been characterized in contract NAS 8-35614. The baseline

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Table 7.2-1. OTV Adjustments for 65K LB STS

● RELATIVE TO APRIL 1986 72K LB BASELINE

GB OTV
● INCREASE GB OTV SINGLE LAUNCHES BY 13
● INCREASE GB OTV DUAL LAUNCHES BY 2
● COST IMPACT: $1374 MILLION

SB OTV + EXISTING
UPPER STAGES
● INCREASE PROP TANKER FLIGHTS BY 8
● COST IMPACT: $612 MILLION

GB OTV + SB OTV
● INCREASE GB OTV SINGLE LAUNCHES BY 13
● INCREASE SB OTV FLIGHTS BY 2
● INCREASE PROP TANKER FLIGHTS BY 2
● COST IMPACT: $1285 MILLION

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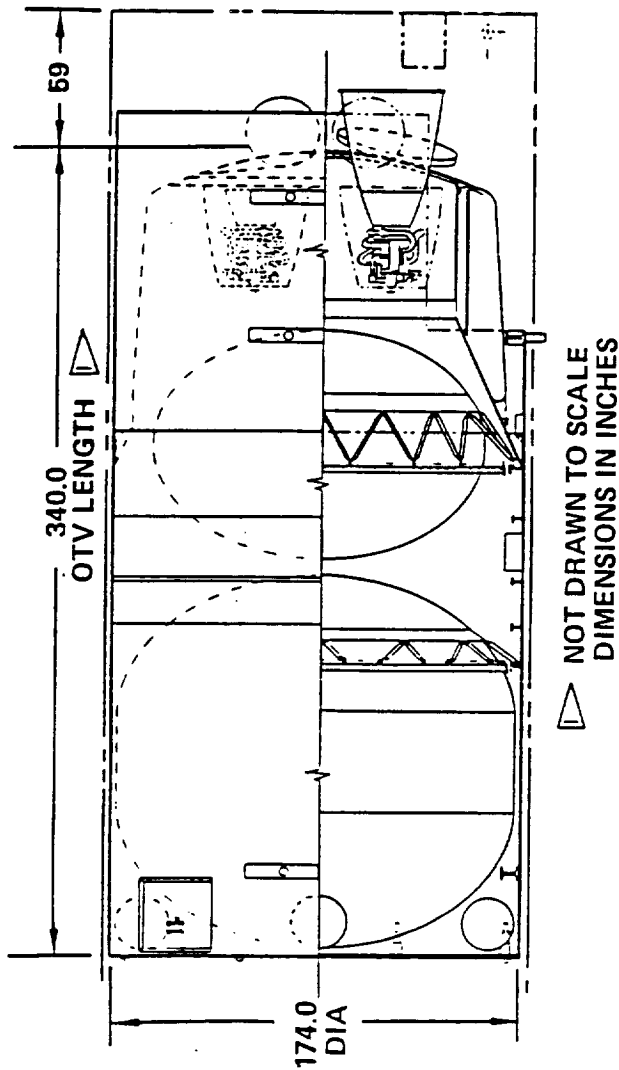
FEATURES

- LAUNCHED AND RETURNED IN ORBITER CARGO BAY

- BALLUTE AEROASSIST—EXPENDABLE
  - 33 FT. DIA FOR MAIN STAGE RETURN
  - 36 FT. DIA FOR RETURN W/SMALL AUX TANKS
  - 43 FT. DIA FOR RETURN W/LG. AUX TANKS
  - 67 FT. DIA FOR RETURN OF AUX. TANKS & CREW MODULE

- ADVANCED CRYO ENGINES, T = 5000 LBF EACH

- 2 TANKS

WEIGHT SUMMARY (LBM)

	MAN-RATED SCAR (33 FT. BALLUTE)	MAN-RATED (67 FT. BALLUTE)
● DRY	7,784	9,684
● MAIN PROP (TOTAL)	40,850	40,850
● OTHER FLUIDS	1,173	1,242
● START BURN	49,807	51,776

Figure 7.2-1 GB SCB OTV Configuration Update — 65K Orbiter Launch

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Table 7.2-2 GB SCB OTV Weight Summary

MAIN STAGE SIZED FOR 65K STS

	9K LB GEO DELIV. [1]	12K LB GEO DELIV.	20K LB GEO DELIV.	7.5K LB MANNED RETURN
STAGE DRY WEIGHT	7,784	7,886	8,151	9,684
AUX. TANK DRY WEIGHT	—	2,449	3,286	3,286
TOTAL MPS PROPELLANT	40,850	55,620	73,840	82,590
OTHER FLUIDS	975	1,345	1,542	1,804
PAYLOAD	9,000	12,000	20,000	7,500
START-BURN WEIGHT	58,609	79,300	106,819	104,864
ASE	6,391	[2] 10,975	[2] 10,975	[2] 10,975
ACC	—	—	—	—
TOTAL LAUNCH WEIGHT	65,000	90,276	117,794	115,839

[1] 65K LB STS LIMIT SIZING

[2] REFLECTS ASE FOR TWO STS LAUNCHES (1ST—P/L + AUX. TANK; 2ND—STAGE)
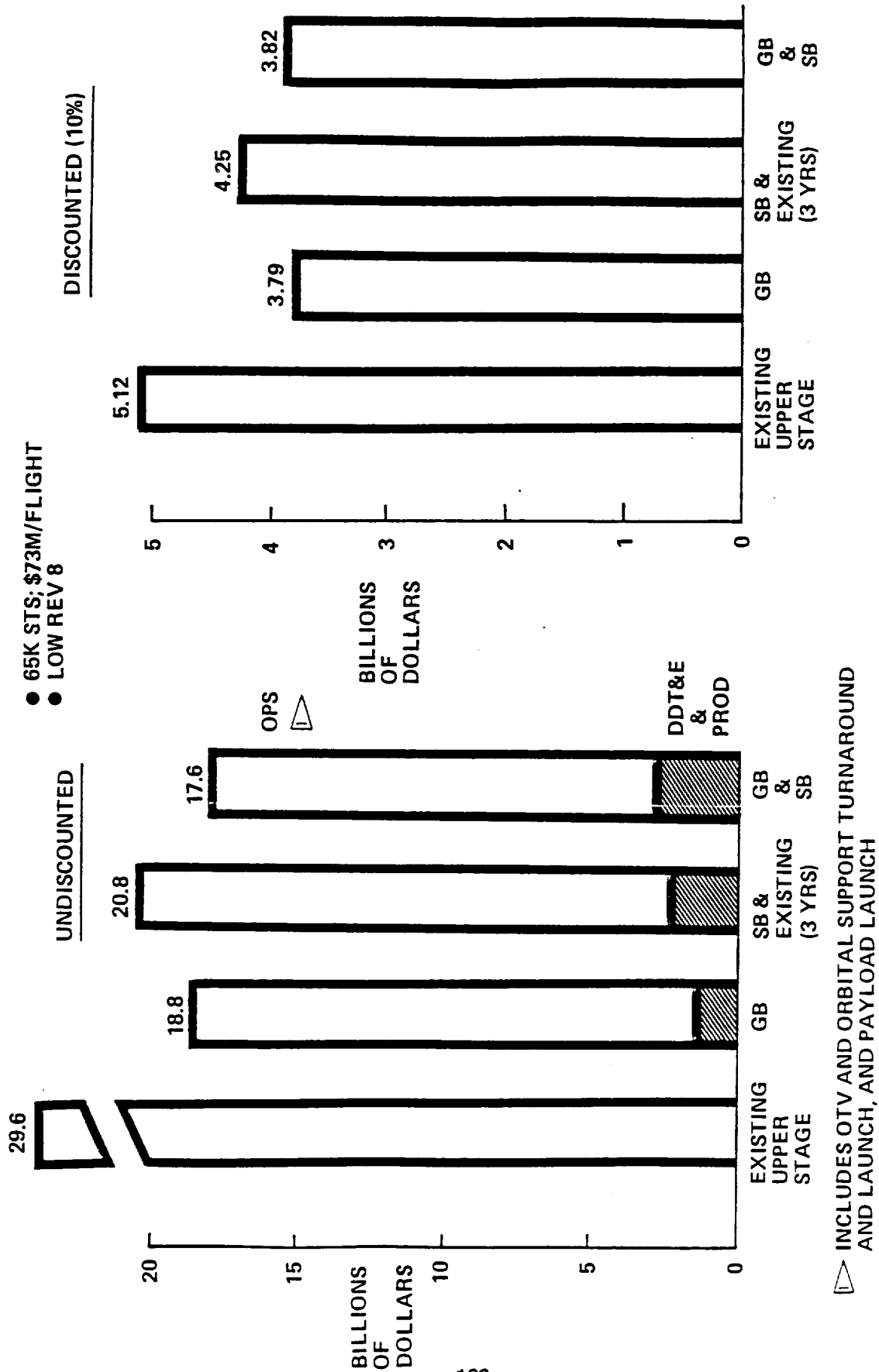
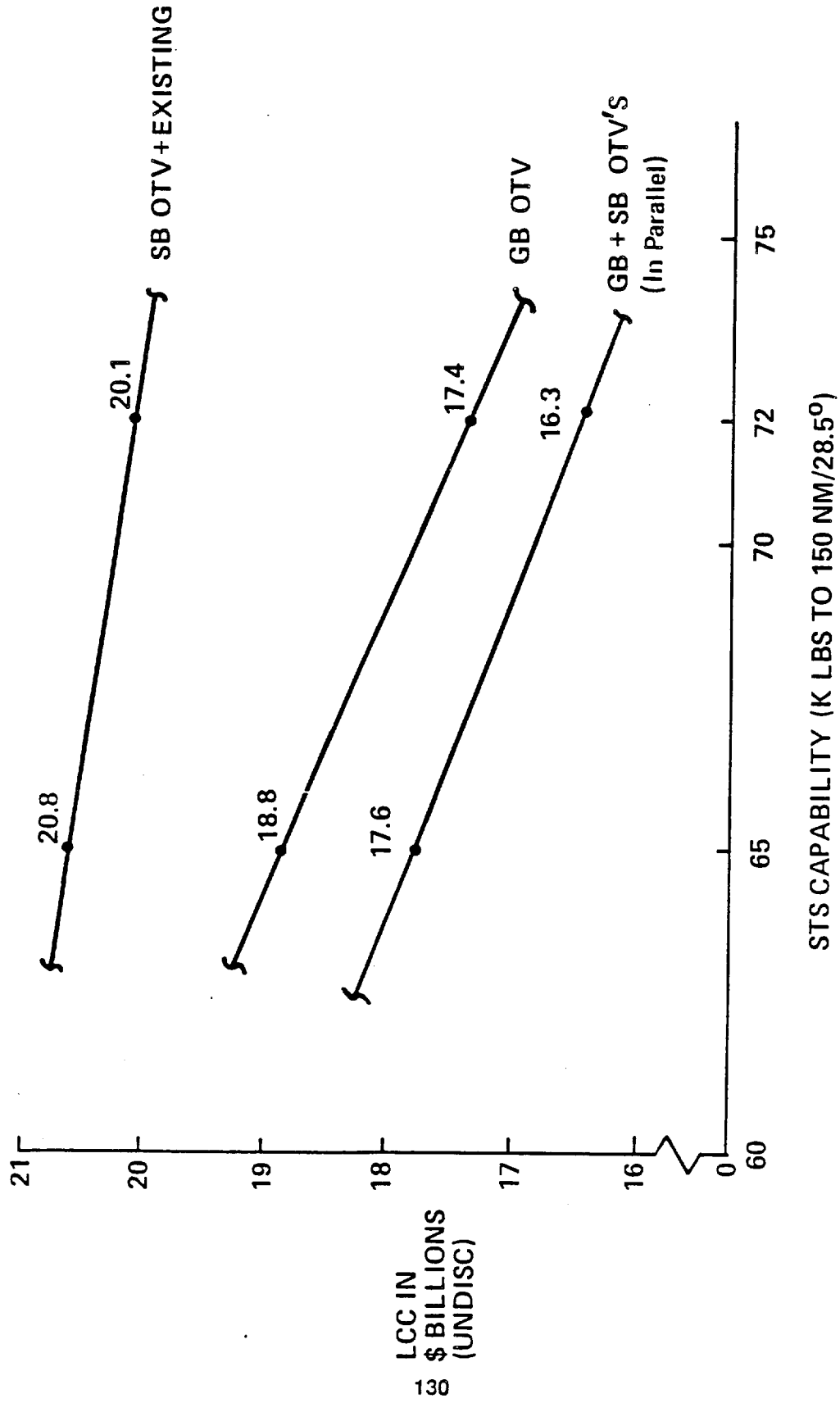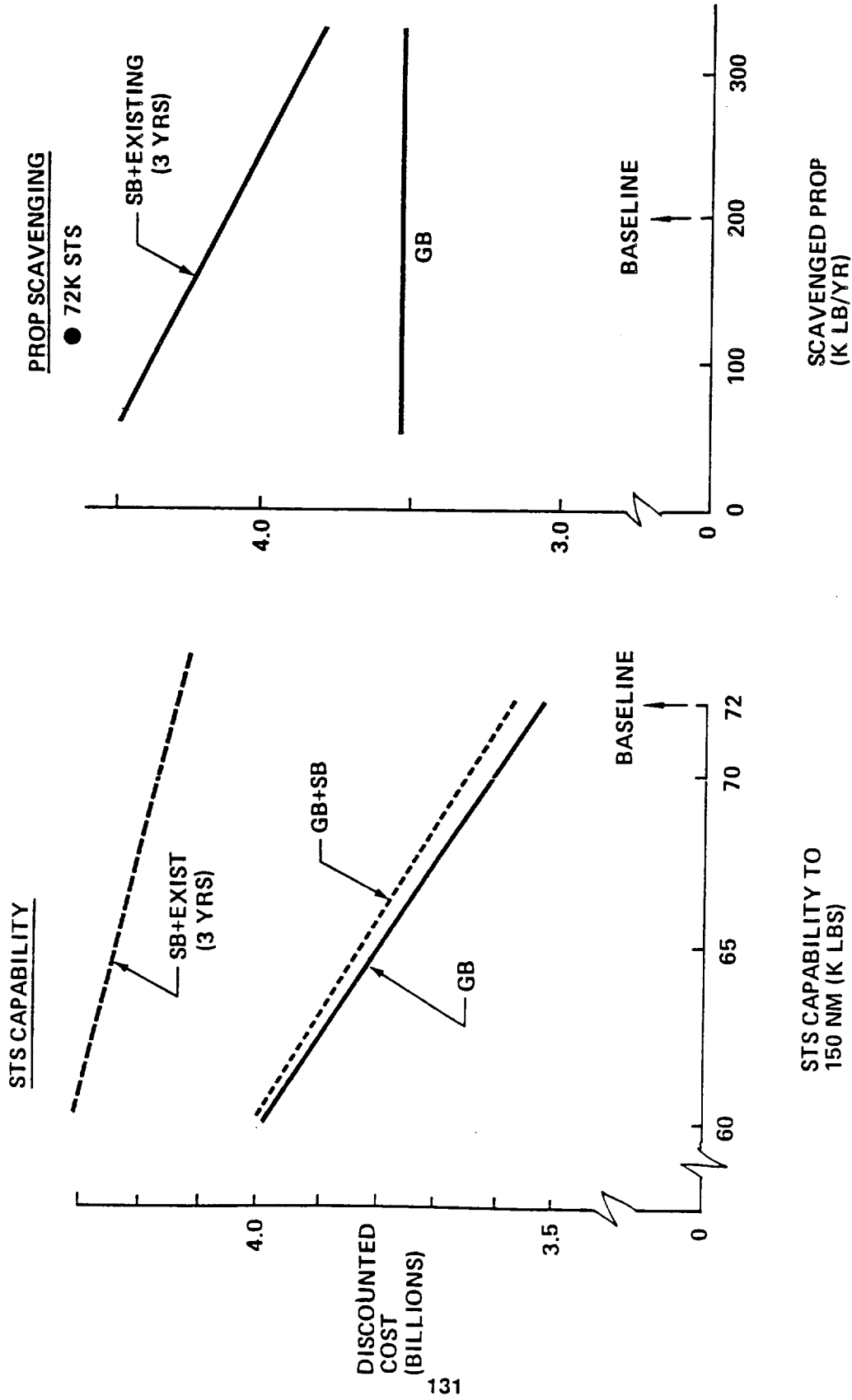*Figure 7.2-2 OTV Basing Trade — OTV Program LCC Comparison*

Figure 7.2-3 Basing Trade Sensitivity to STS Performance

Figure 7.2.4 Basing Trade Sensitivities Phase I

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comparison used an ACC for holding the scavenging tanks and provided an average of 14K lbm per STS flight for a total of 200K lbm per year. The DDT&E cost for the system including ACC was $240 million and 10 scavenging tank set systems had a production cost of $107 million. The average recurring cost (refurb of tank set plus the expendable ACC hardware) was $250 per pound of delivered propellant. Per study ground rules, there was no STS users charge associated with the delivery of the propellant. The basing trade LCC sensitivity to the amount of scavenging propellant is shown in figure 7.2-5 (undiscounted). The discounted cost was previously shown in figure 7.2-4. For the 72K-STS, and discounted costing, the scavenging propellant quantity must go from 200K lbm to nearly 500K lbm per year for the SB OTV concept to equal the cost of the GB OTV. Should a 65K STS be employed, the undiscounted LCC breakeven point would be a scavenging quantity of approximately 300K-lbm. If no scavenging is available or if transportation cost is included the SB OTV option gets significantly worse.

7.2.3 OTV Flight Rate

The last basing option sensitivity to be discussed is that of OTV flight rate. The results of this sensitivity are presented in figure 7.2-6. The baseline Rev. 8 low mission model involved 145 OTV flights and the nominal model had 265 flights. The cost per flight indicated for each basing option is the composite value for all the missions in the model. Because the SB OTV option has a higher average cost per OTV flight it is obvious that larger mission models in terms of number of flights will not result in this option being the least cost. What could change the cost result in terms of mission model would be a major change in composition; that is a higher percentage of heavy and long payloads and more round trips. Such a model would penalize the GB OTV option and enhance the cost characteristics of the SB OTV option. However, as with the current models a combination of GB plus SB OTV's would most likely still result in the least cost because there will be missions best adapted to one or the other of the OTV's.

7.3 OVERALL ASSESSMENT AND RECOMMENDATION

The assessment of the basing trade options is presented in table 7.3-1. The recommendation at this time is to begin with a reusable ground based OTV consisting of only a main stage. To satisfy more demanding missions after the turn of the century, several options are available depending on the specific nature of the mission requirements. Those options are to add either an auxiliary propellant tank to the inventory or develop a full fledged SB OTV to be used in conjunction with the GB OTV. Use of the auxiliary tank is our current baseline and will result in a minimum scar to Space Station
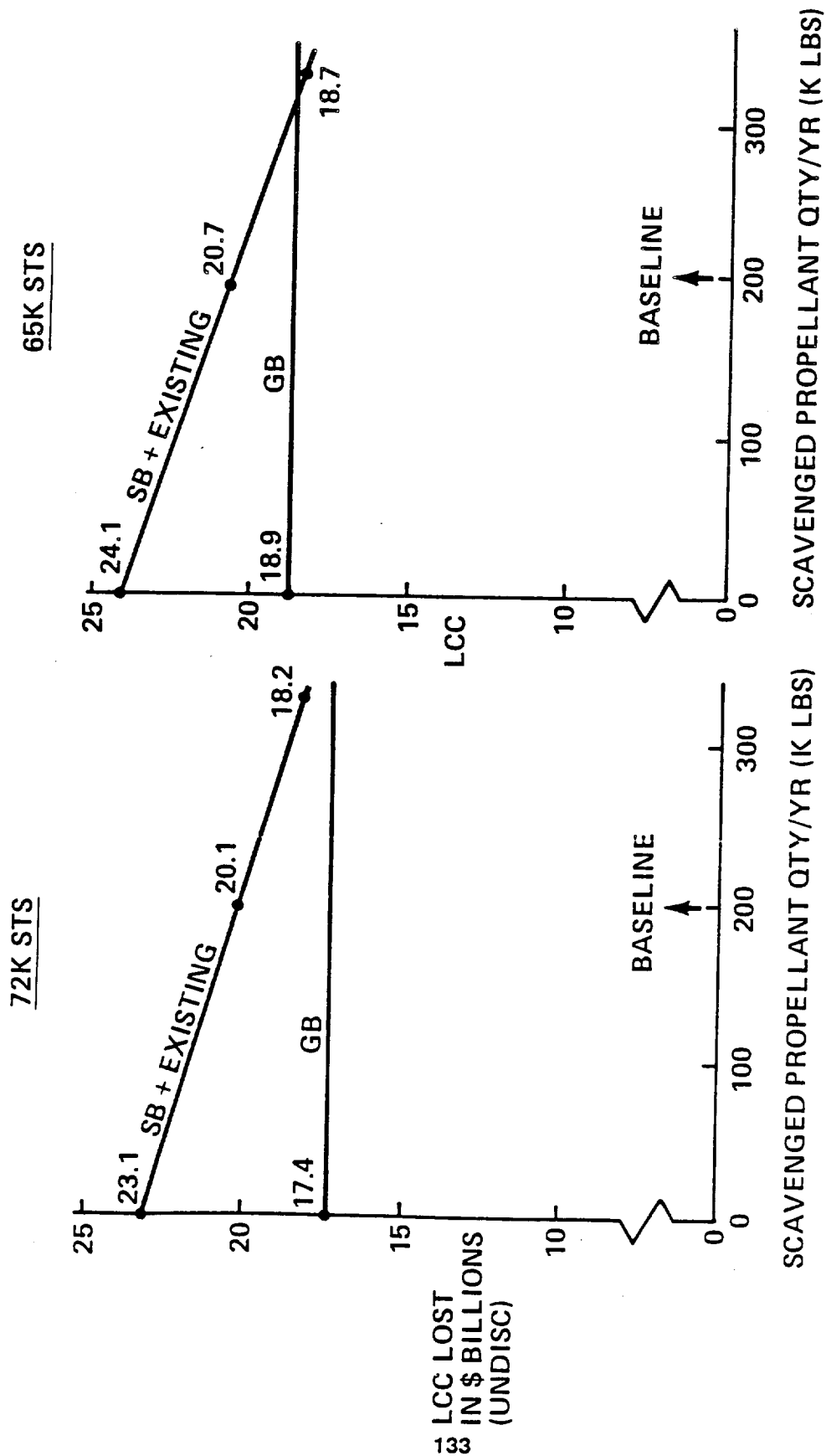
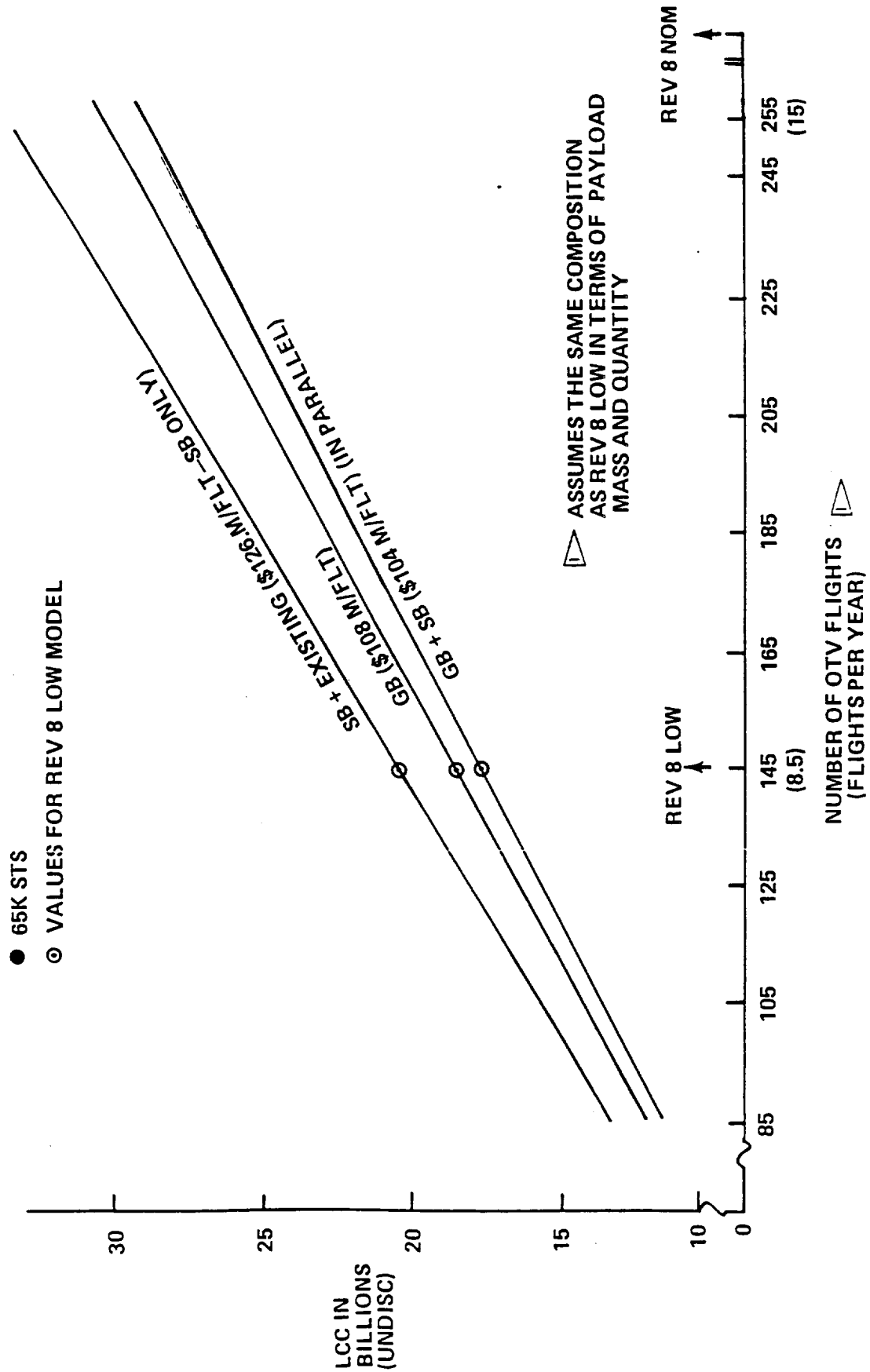Figure 7.2-5 Basing Trade Sensitivity to Propellant Scavenging

Figure 7.2.6 Basing Sensitivity to OTV Flight Rate

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Table 7.3-1 Recommendation OTV Basing

- GROUND BASED ONLY OR GROUND BASED IN PARALLEL WITH SPACE BASED

- BEGIN WITH GROUND BASED OTV AND CONTINUE USING THROUGHOUT PROGRAM FOR PAYLOADS ≤ 12K LBS

- TWO VIABLE OPTIONS FOR SATISFYING MORE DEMANDING MISSIONS OCCURRING AFTER YEAR 2000

  - ADD AUXILIARY PROPELLANT TANK TO GB OTV WITH PHYSICAL INTEGRATION OCCURRING AT STATION

  - OR DEVELOP AND USE IN PARALLEL A SPACE BASED OTV

- EITHER APPROACH PROVIDES A 16% AND 11% DISCOUNTED LCC SAVINGS OVER SB OTV + EXISTING STAGES FOR 72K LB STS AND 65K LB STS, RESPECTIVELY

- PROVIDE A 16% LOWER COST PER FLIGHT

- MINIMIZES OR DELAYS SCAR TO SPACE STATION

- ALLOWS REUSABLE OTV PROGRAM TO BEGIN SOONER

hardware and operations as only the physical integration of the main stage and auxiliary tank/payload are involved. Either of these two options provide LCC and cost per flight, and DDT&E advantages over a pure SB OTV option and over continued use of existing upper stages. In addition, because the concept does not require early use of the Space Station it has the potential to have an IOC as early as 1994. However, should data become available that indicates the eventual need of a SB OTV, the GB OTV provides a good evolutionary path.

8.0 PROGRAM EFFECTIVENESS

The effectiveness of a reusable OTV program relative to an existing all expendable upper stage fleet was shown in section 7.0 when considering a total mission model. Another measurement of effectiveness is the comparison of the reusable OTV and expendable stage based on delivery cost to the payload. This comparison using the main stage of the GB OTV is presented in figure 8-1.

The results indicate that for payloads currently delivered by PAM upper stages the total cost including launch per payload is $27.3 million in 1985 dollars. The GB OTV main stage has the capability to deliver four of these payloads on one flight yielding an average cost to the payload of $20 million which includes launch, OTV unit cost amortization, OTV turnaround cost and payload integration. Compared to PAM DII delivery, the OTV provides a $4 million per payload margin with three payload delivered on one flight and in addition the OTV has nearly 2000 lbs of payload margin. The OTV is capable, from a mass standpoint, of delivering two IUS class payloads which would reduce the cost to each payload by nearly $80 million. One 10,000 to 12,000 lbs Centaur equivalent payload could be delivered by the OTV which would reduce the payload delivery cost by nearly $50 million. Expressed as cost per pound of payload to GEO the GB OTV yields $6,600/lb versus $10,000/lb for Centaur.

In summary, because of reusability and good performance characteristics payloads can be delivered in a cost effective manner with a new generation reusable orbit transfer vehicle. It should be noted however that a new expendable was not considered in the Phase I analysis, but was investigated in Phase II and reported in Volume IX.
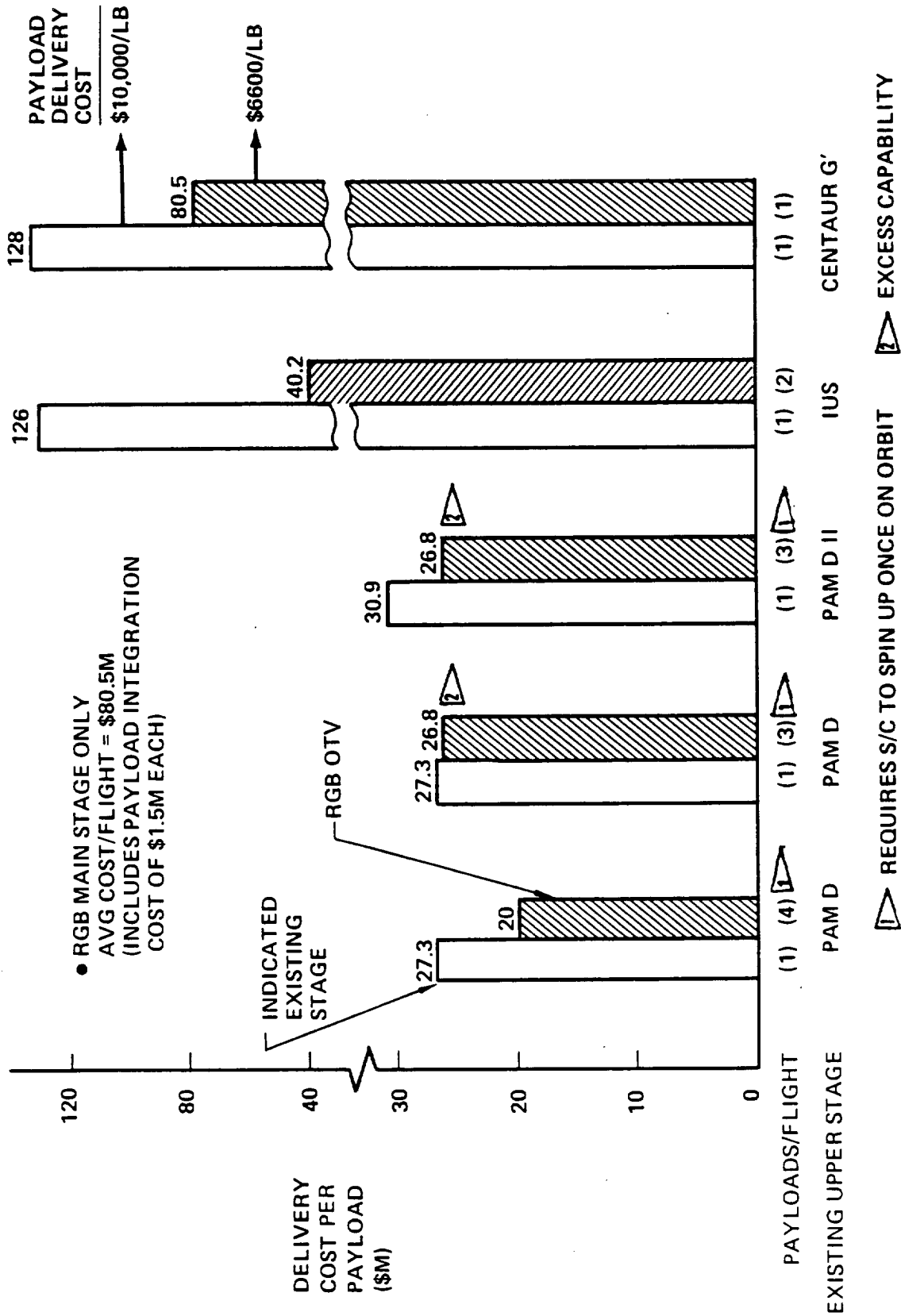
Figure 8-1. Payload Delivery Cost Comparison

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